MODELLING OF MICRO WIRE ELECTRO DISCHARGE MACHINING IN AEROSPACE MATERIAL

A Thesis Submitted to

National Institute of Technology, Rourkela
(Deemed University)

In Partial fulfillment of the requirement for the degree of

Master of Technology
in
Mechanical Engineering

By

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Rourkela -769 008 (India)

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Under the guidance and supervision of

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National Institute of Technology
Rourkela

CERTIFICATE

This is to certify that the thesis entitled **—MODELLING OF MICRO WIRE ELECTRO DISCHARGE MACHINING IN AEROSPACE MATERIAL** submitted to the National Institute of Technology, Rourkela (Deemed University) by **Anshuman Kumar**, Roll No. **210ME2237** for the award of the Degree of **Master of Technology** in **Mechanical Engineering** with specialization in **—Production Engineering** is a record of bonafide research work carried out by him under my supervision and guidance. The results presented in this thesis has not been, to the best of my knowledge, submitted to any other University or Institute for the award of any degree or diploma. The thesis, in my opinion, has reached the standards fulfilling the requirement for the award of the degree of **Master of technology** in accordance with regulations of the Institute.

Place: Rourkela

Date:

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Date: **(Anshuman Kumar)**

Nomenclature

EDM	Electrical discharge machining
WEDM	Wire Electrical discharge machining
MRR	Material removal rate (mm^3/min)
H_i	heat input to the workpiece
V	Voltage (V)
I	Current (Amp)
Q(r)	Heat flux (W/m^2)
R	Spark radius (μm)
x	Radial coordinate
K	Thermal conductivity (W/mK)
T	Temperature variable (K)
T0	Initial temperature (K)
Ton	Spark-on time (μs)
T_{off}	Spark-off time (μs)
x,y	Cartesian coordinate of workpiece
C_p	Specific heat (J/kgK)
C_v	Crater volume (μm3)

Abstract

During the last decade there has been continuing demand of compact, integrated and small size products by a non-traditional process for accurate and cost-effective measurement of material properties. These are needed for machining for tools and product design, the development of micro size components, the growing needs for micro-feature generation. Micro-manufacturing processes have different material capabilities and machining performance specifications. Machining performance specifications of concern include minimum feature size, tolerance, surface finish, and material removal rate (MRR) and applications of advanced, which is very difficult-to machine materials. They have made the wire EDM an important manufacturing process to meet these demands. Wire electrical discharge machining (WEDM) technology has been widely used in production, aerospace/aircraft, medical and virtually all areas of conductive material machining. Aerospace materials are known as unique materials ever produced in manufacturing industries. It's capable to withstand in very high temperature and the excellent resistance in mechanical and chemical debilitate. The aerospace material is nickel based superalloys is having high strength, thermal conflict with very tough material characteristics. It is also very good in corrosion resistance in many conditions of engineering applications. Due to very tough in nature and the machinability has been studied by many researchers on these materials and been carried out for last few years. This project presents the machining of the aerospace materials using wire EDM with in micro size. The objective of this project is to investigate the performance of micro wire EDM machining on aerospace materials. WEDM is extensively used in machining of conductive materials when accuracy and tight tolerance is important. Zigzag cutting operation in wire EDM is treated as challenging one because improvement of more than one performance is measured. Simple and easily understandable model for an axisymmetric 2D model for wire electric discharge machining (WEDM) has been developed using the finite element method (FEM). The observation have been influenced on various characteristics namely, material removal rate (MRR) and residual stress. A full factorial design of experiment (DOE) approach with two-level, three factorials is employed to conduct this experiment. Mini tab software was used to perform the ANOVA analysis and confirmation test was also conducted to verify and compare the results from the theoretical prediction using software.

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1.1 Project Background.

Electrical discharge machining (EDM) is a non-conventional machining concept which has been widely used to produce dies, molds and metalworking industries. This technique has been developed in the late 1940s and has been one of the fast increasing methods in developed area during 1980s and 1990s [1].

This machining method is commonly used for very hard metals that would be impossible to machine with conventional machine. It has been widely used, especially for cutting complicated contours or delicate cavities that also would be tough to produce with conventional machining methods. However, one critical limitation is that EDM is only works with electrically conductive materials. Metal that can be machined by using EDM include nickel-based alloy (such as aerospace material), very hard tool steels etc.

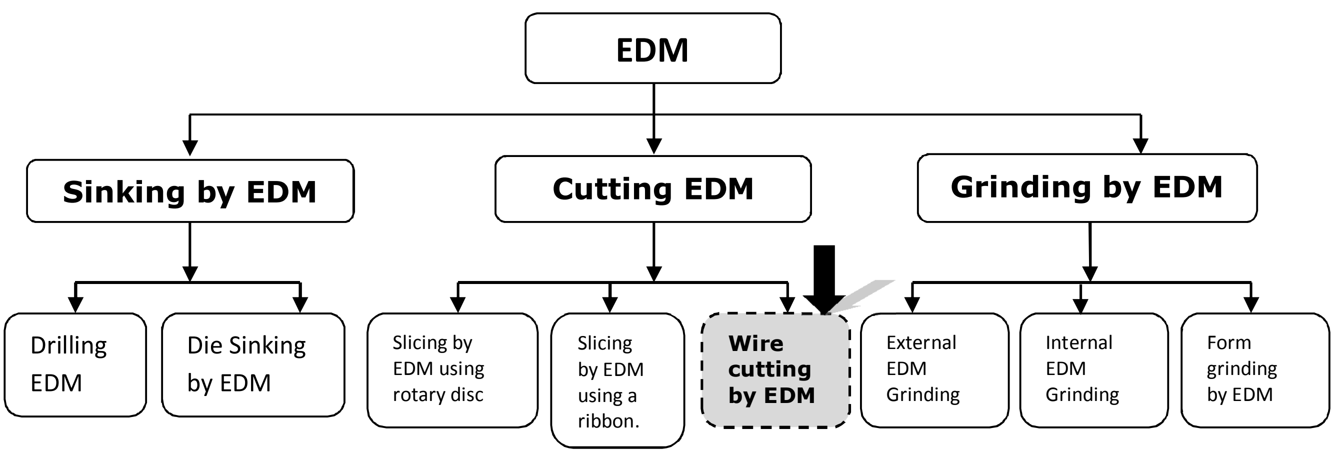


Fig. 1: Types of EDM processes [5]

Wire electrical discharge machining (WEDM) was introduced in the late 60's. The procedure was fairly simple, not very difficult and electrically conductive material wire choices were limited to copper and brass etc. WEDM is a thermo-electrical process in which material is 2 eroded from the work material by a series of separate sparks between the work material and the wire electrode i.e. tool (wire) and workpiece material, separated by a thin film of dielectric fluid (distilled water oil) that is continuously fed to the machining zone to flushing away the evaporated particles. The movement of wire is controlled numerically to achieve the desired 3D (3-dimensional) shape and accuracy of the workpiece . The degree of accuracy of work material dimensions reachable and the fine surface finishes make WEDM mainly valuable for applications involving manufacture of, extrusion dies, etc. Without this, the fabrication of precision work material requires lot of time for labor-intensive grinding, polishing as well as cutting.

In recent years, the technology of micro wire electrical discharge machining (WEDM) has been improved rapidly to meet the requirements in market, especially in the casting industry. WEDM is being used to machine a wide variety of miniature and micro-parts from metals, alloys, silicon etc. This tremendous achievement in WEDM technology has been achieved by many researchers from some of the world leading research institute.

The Spark Theory on a wire micro EDM is basically the same as that of the vertical EDM process. Wire EDM has wide area of applications like in aerospace, nuclear area, industrial field, automobile field, etc. In wire Electrical Discharge Machining, the conductive materials are machined with a continuous of electrical discharges (sparks) that are produced in between an accurately positioned moving wire (Electrode) and the work material. High frequency pulses of AC or DC current is discharged from the wire to the work material with a very small spark gap through dielectric medium (distilled water). Wire EDM uses a continuously running thin wire as the electrode and this is very useful for cutting profiles in plates.

The most important difference between micro wire EDM and wire EDM is the dimension of the plasma channel radius that is produce during the spark: in conventional wire EDM is much smaller than the electrode (wire) but the size is comparable for micro wire EDM [5].

Wire EDM often uses a steel wire that has been coated with brass, tungsten wire and other materials of good conductivity, with high strength and high melting temperature. The electrode material (wire) has to be matched to the work material so that in-process variations are controlled accurately. This is critical for achieving micro tolerances, especially when the spark gap can be as big as 30 microns.

Some key aspects to machine with small electrodes can be extracted from the presented ideas of (WEDM) [1, 2]:

- Control the pulse energy
- Control the wire traction force
- Increase the gap stability obtained by the control (avoid discharge fluctuations)
- Increase the machine positioning accuracy.

For micro wire EDM, the entire machine, the electrodes, the programme, the control, the measuring instruments and the operators play an important role in the process [3].

Micro wire EDM is particularly suitable to making small parts with very tight tolerances and with good quality of surfaces finish. The process concept is not very different to conventional EDM.

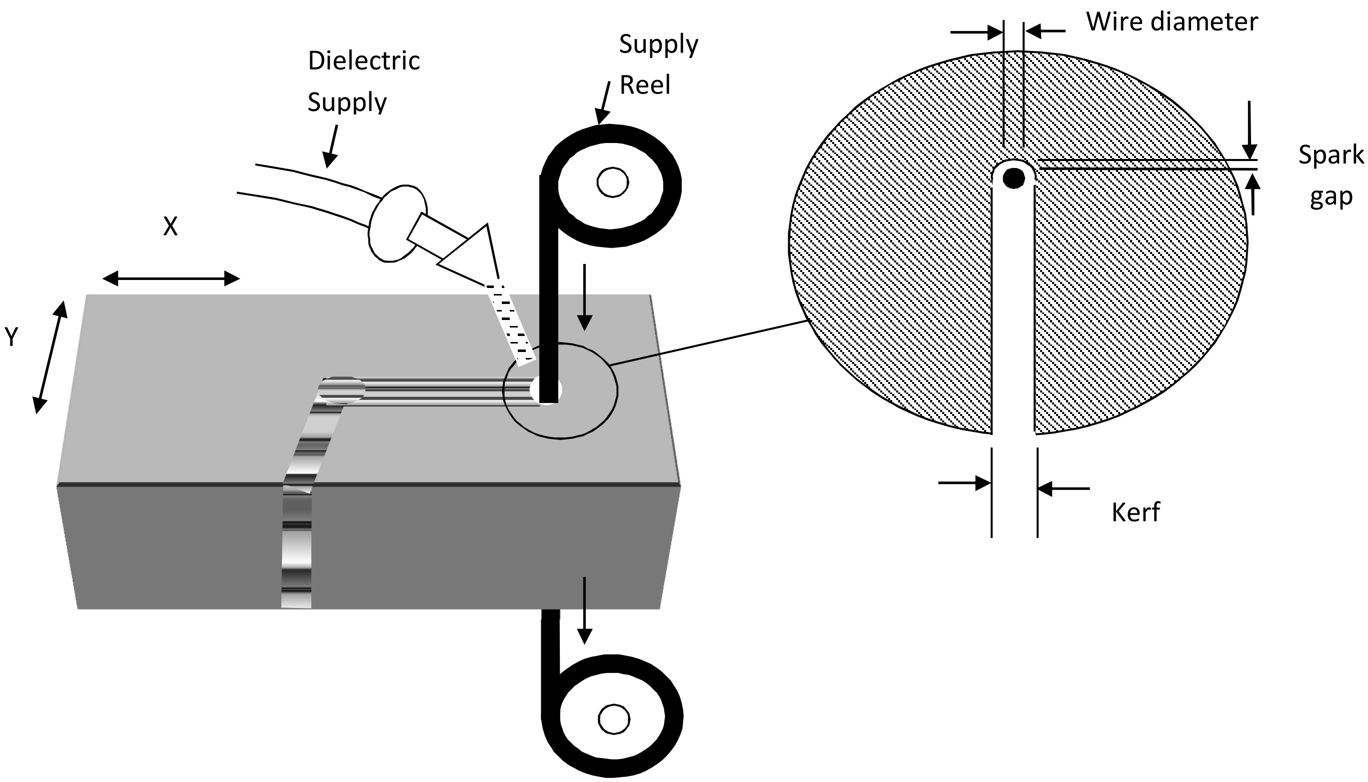


Fig. 2 Cutting mechanism in Wire EDM [8]

The main concept of WEDM is shown in Figure 2. In this process, a gently moving wire passes through a recommended path and removes material from the workpiece. WEDM uses electro-thermal mechanisms to cut electrically conductive materials. The material is removed by a continuous of sparks between the wire electrode and the work material in the presence of die-electric (distilled water), which creates a path for each discharge as the fluid becomes ionized in the gap between tool (wire) work material. The area where discharge takes place is heated to extremely high temperature, so that the surface is evaporated and removed. The removed particles are flushed away by the flowing dielectric which shown in Figure 3. The wires materials for WEDM are made of brass, copper, tungsten, etc. (0.02 – 0.3mm in diameter) which capable to achieve very small corner radii. The wire used in WEDM process should be high tensile strength and very good electrical conductivity.

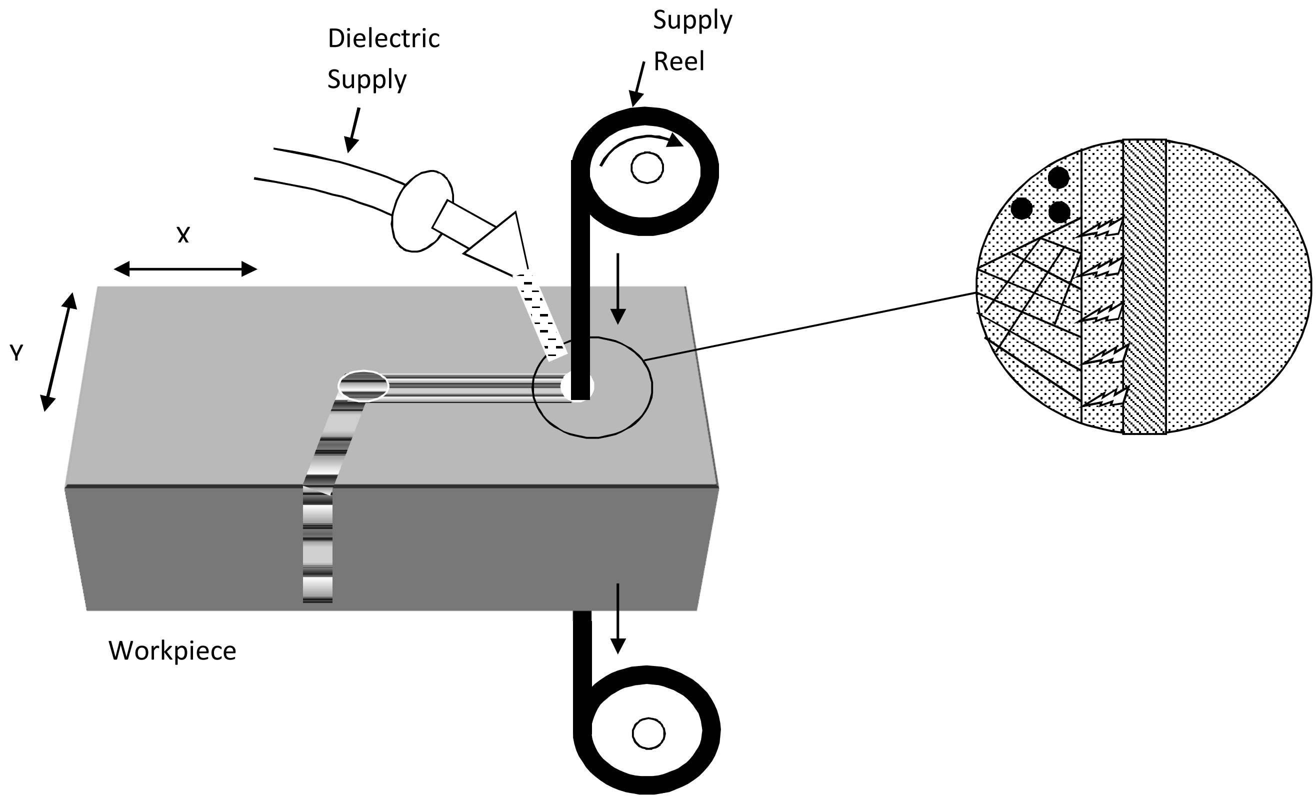


Fig. 3: Schematic of the thermal removal process of WEDM [5].

WEDM process is usually used in combination with CNC and will only work when a part is to be cut completely through. The melting temperature of the parts to be machined is an important factor for this process rather than strength or hardness. The surface quality and MRR of the machined surface by wire EDM will depend on different machining factors such as applied peak current, and wire materials. WEDM process is commonly conducted on underwater condition in a tank fully filled with dielectric fluid.

While both conditions (submerged or dry machining) can be accomplished, very important is to produce a good quality of surface roughness and dimensional accuracy. The main goals of micro WEDM are to achieve a better stability and higher productivity of the micro WEDM process. As newer and more exotic materials are developed, and very complex shapes are required, conventional machining operations are continually reaching their limitations but on the other hand the uses of micro WEDM in manufacturing area will continue to increasing [6]. However, due to a large number of variables in micro WEDM, it is difficult to achieve the optimal performance of micro WEDM processes [6] and the effective way of solving this problem is to establish the relationship between the performance measures of the process and its controllable input parameters.

1.2 Objectives

The objectives of the project work are:

- To determine the significant parameters that influences the machining responses during Micro Wire Electro-Discharge Machining (micro WEDM) of Aerospace material.

- Determine the temperature distribution of tool and work piece by developing a thermal-electrical model for sparks generated by micro wire electrical discharge in a liquid media.

- To evaluate the performance of micro Wire Electro-Discharge machining (micro WEDM) on aerospace material with respect to various responses such as spark gap, material removal rate, cutting speed and kerf width.

Chapter 2

- **Literature review**

Z. Katz et al (2004) investigated the effects of micro EDM model was proposed along with numeric simulation and experimental proof. This work is aimed at relating input/output constraints towards the establishment of a possible process model. It makes use of dimensionless groups connected and relevant to micro electro discharges and their effect on metal removal during the process. The reasons for their selection are discussed and problems related to micro discharges are explained. An electric circuit used for the controlling of the discharge is presented and explained. A precise output is used as an example for the model, as suggested [53].

Tian et al has studied towards process monitoring and control of micro wire EDM process by developing a new pulse refinement & control system. This system functions by detecting 4 major gap states classified as open circuit, normal spark, arc discharge, and short circuit by detecting the characteristics of gap voltage waveforms. The effect of pulse interval, machining feed rate, and workpiece thickness on the normal ratio , arc ratio & short ratio. It could be concluded from the experiment that a longer pulse interval would result in increase of short ratio at constant machining feed rate. A high machining federate as well as increase of work piece height results in increase of short ratio [56].

J. Prohaszka et al (1996) proposed that requirements of the materials used for WEDM electrodes that will lead to the improvement of WEDM performance. Experiments had been conducted regarding the choice of suitable wire electrode materials and the influence of the properties of these materials on the machinability in WEDM. He had discussed in this paper that the material requirements for fabricating WEDM electrodes for improving WEDM performance. Experiments were carried out regarding the choice of suitable wire electrode materials the effect of the materials properties of the wire on the machinability in WEDM being presented. He had evaluate the influence of the various materials used for the fabrication of wire electrodes on the machinability during WEDM, a series of boring experiments had conducted on a standard Electro Discharge Machine-unit. Negative polarity rods of pure magnesium, tin and zinc and of a diameter of 5.0 mm were used as the tool electrodes. The workpiece (anode) was annealed non-alloyed steel with low carbon content. The operational parameters were kept constant during the whole series of experiments [20]

Prasad Bari et al (2012) proposed that Electrical discharge machining (EDM), researchers have explored a number of ways to progress and optimize the MRR including some unique experimental models that depart from the traditional EDM sparking singularity. Despite a range of different styles, all the research work in those area segments the same objectives of reaching more efficient material removal rate (MRR) coupled with decline in tool wear rate (TWR) and improved surface quality. They approaching with outcome the best suitable dielectric fluid for a given workpiece and tool material in order to increase MRR and reduce TWR. Their paper also deals with the effects powder mixed dielectric fluid on MRR and TWR. And the researchers conclude their study by the effect of powder mixed dielectric fluid on MRR and TWR will be seen experimentally. MRR and TWR for various powders will be compared [13]

Scott F. Miller et al (2005) investigated the effects of wire electrical discharge machining (EDM) of cross-section with minimum thickness and acquiescent mechanisms was studied. Effects of EDM process considerations, particularly the spark cycle time and Ton on thin cross-section cutting of Nd–Fe–B magnetic material, carbon bipolar plate, and titanium were investigated. An envelope of feasible wire EDM process parameters was created for the commercially pure titanium. The application of such cover to select suitable EDM process parameters for micro feature generation was established. Applications of the thin cross-section EDM cutting for manufacture of compliant mechanisms ware discussed.

They concluded there research by the Effects of spark cycle and Ton on wire EDM micro structures were investigated. Tests were conducted on various materials for minimum thickness wire EDM cutting. The researcher study presented the needs of meticulous thermal and electrostatic stress modeling for micro EDM, particularly for components with miniature feature size. Although results presented were machine-dependent, this research delivers the guidelines and techniques for the development of wire EDM process to manufacture minute features on advanced engineering materials [13, 14, 15, 16, 17].

H.K. Kansala et al (2008) proposed a simple and easily reasonable model for an axisymmetric two-dimensional model for powder mixed electric discharge machining (PMEDM) has been developed using the FEM. The model utilizes the several important features such as temperatures sensitive material properties, shape and size of heat source (Gaussian heat flux distribution), % distribution of heat among tool, workpiece and dielectric fluid, pulse on/off time, material discharge efficiency and phase change (enthalpy) etc. to forecast the thermal behavior and material removal mechanism in PMEDM process. The developed model first calculates the temperature dispersal in the workpiece material using ANSYS software and then material removal rate (MRR) was predictable from the temperature profiles. The effect of various process parameters on temperature circulations along the radius and depth of the workpiece has been reported. Finally, the model has been validated by relating the theoretical MRR with the experimental one attained from a newly designed experimental setup industrialized in the laboratory [12].

P.K. Mishra et al (1993) described the application of wire-cut EDM process is used in industry for the production of strategies such as punches, dies, stripper-plates of very hard metals and alloys and whatever. However, the frequent existence of rupture of the wire is one of the most serious production restraints in EDM wire cutting. The marvel restricts the cutting speed, increases the machining time and affects the surface finish and accuracy adversely. The probable causes foremost to wire rupture are failure under thermal load, failure through short-circuiting and wire vibration, the most significant among these being the thermal load. It is, therefore, essential to be able to predict wire failure under extreme thermal loads so that this situation can be escaped in actual operation and the performance efficiency thus improved. The main objective of this study was to decide the temperature distribution in the material of the wire and thereby to expect failure due to thermal load. In this study, a simple computational model is established which will give the temperature values for varying magnitudes of factors, viz., input power, Ton, wire velocity and wire diameter. It was hoped that the optimal control of these parameters will help in preventing thermal failure, thus obtaining better consumption of the process. A finite-difference thermal model to expect the temperature distribution along the wire for the wire-EDM procedure in the zone of the discharge channel is proposed. The power is supposed to be degenerate in a single spark through a volumetric heat source present within the wire over the discharge channel width, which, in turn, was planned from the available literature [24]

S. S. Mahapatra et al (2007) presented wire electrical discharge machining (WEDM) was widely used in rough cutting operation in WEDM is treated as a interesting one because improvement of more than one machining performance measures viz. metal removal rate (MRR), surface finish

(SF) and kerf width are sought to obtain a precision work. Using Taguchi's parameter design, it had been detected that a combination of factors for optimization of each enactment measure is different. In this study, the association between control factors and responses like MRR, SF and kerf are recognized by means of nonlinear regression investigation, resulting in a valid mathematical model. Finally, genetic algorithm, a popular evolutionary method, was employed to enhance the wire electrical discharge machining method with multiple objectives. The study establishes that the WEDM process parameters can be familiar to achieve better MRR, surface finish and cutting width simultaneously.[11]

Liao et al had discuss about the wire rupture in the WEDM process is a thoughtful problem to manufacturers. A new computer-aided pulse taste system based on the characteristics of voltage waveform during machining was established. With the use of this system, a large amount of sparking frequency data during wire split process and under normal working conditions were collected and investigated. Two symptoms of wire rupture were known: the excess of arc sparks, and a rapid rise of the total sparking frequency. The governing mechanisms of these two types of wire rupture were established from the SEM and EDAX analyses of the split wire electrode. Also, an index to monitor wire breaking was recognized, and its relationships with the metal removal rate and machining parameters were establish. Based on the results obtained in the paper, a control strategy to thwart wire from rupturing while at the same time improving the machining speed is proposed [23].

G. L. Benavides et al had discussed about Micro-EDM is a subtractive meso-scale machining process. The Agie Excellence 2F wire micro EDM is accomplished of machining with a 25 micron diameter wire electrode and locating the work piece to within ±1.5 microns. This study was done to study the machining performance of the wire micro EDM process by machining a high aspect ratio meso-scale part into a variety of metals (e.g. 304L stainless steel, Nitronic 60 Austentic Stainless, Beryllium Copper, and Titanium). Machining performance factors such as, profile tolerance, perpendicularity, and repeatability are related for the different materials. Pertinent examination methods desirable for meso-scale value assurance tasks are also estimated. Although the wire EDM process is normally used to fabricate 2½ dimensional features, these features can be machined into a 3D part having other features such as hubs and chamfers to simplify assembly [40]

Chapter 3

- **Modelling of micro WEDM**
  - Modeling procedure using ANSYS
  - Process of Thermal Modeling using ANSYS® software
  - Modeling of MRR of μ wire EDM
  - Measuring residual stress caused by Wire EDM
  - Coupled thermal-structural finite element simulation

3 Modeling procedure using ANSYS of micro-Wire Electrical discharge machining.

In the wire EDM, a series of rapid, repetitive and randomly discrete electric spark occur in the gap between tool (wire) and workpiece for a cycle of few microseconds. Addition of particles into the dielectric fluid makes this process more complex and random. The following assumptions are made without sacrificing the basic features of the wire EDM model to make the problem mathematically feasible. Firstly one ANSYS model have been developed by taking EDM process, and after getting result it is converted to micro Wire EDM. And taking the workpiece material as Inconel 718, titanium 15 and 5 Cr die steel, model has been developed. After that when get result from ANSYS analysis I comparing the result and compering the MRR for different process parameters.

3.1 Thermal model of EDM to micro Wire EDM

As the working principal is same for both the process, when the distance between the two electrodes (wire and the workpiece) is reduced the intensity of electric field in the volume between the electrodes (wire and the workpiece), become greater than the strength of the dielectric, which breaks, allowing current to flow between the two electrodes. For this reason the spark will generated.

3.1.1 Assumption

The mathematical statement that describes the temperature variation along the wire axis in the wire-EDM process is formulated under the following

Assumptions:

- The model is developed for a single spark.
- For a single pulse the discharge duration and the pulse-on time are assumed to be the same.
- The thermal properties of workpiece material are considered as a function of temperature. It is assumed that due to thermal expansion, density and element shape are not affected
- The work domain considered is axisymmetric
- Temperature analysis is considered to be of transient type [33,34].
- The material of the wire is homogeneous, isotropic and has constant properties.
- The heat source is assumed to have Gaussian distribution of heat flux on the surface of the workpiece [33,34].
- The composition of the material of workpiece is assumed to be homogeneous and isotropic
- Heat source following Jennes et al. [41]. While the heat source/discharge channel diameter (Fig. 4) is a function of the discharge duration, a constant value, corresponding to that at the end of discharge, has been assumed for the entire time period.
- The temperature variation across the diameter of the wire is neglected.
- Joule heating and cross-vibration effects of the moving wire are neglected.
- The workpiece is free from any type of stress before process.

3.1.2 Thermal Model

The discharge phenomenon in wire EDM can be modeled as the heating of the work piece by the incident plasma channel. Fig. 1 shows the idealized case where workpiece is being heated by a Gaussian type of heat source. The mode of heat transfer in solid is conduction.

3.1.3Governing equation

This is the equation for calculation of transient temperature distribution with in workpiece. Heating of workpiece due to a single spark is assumed to be axisymmetric. The differential governing equation of thermal diffusion differential equation in an axisymmetric model is governed by the following

$$\rho C_p \left[\frac{\partial T}{\partial t}\right] = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(K_r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_r \frac{\partial T}{\partial z}\right)\right].. \qquad \text{(i)}$$

Where ρ is density, C_p is specific heat, K_r thermal conductivity of the workpiece, T is the temperature, t is the time and r & z are coordinates of the workpiece.

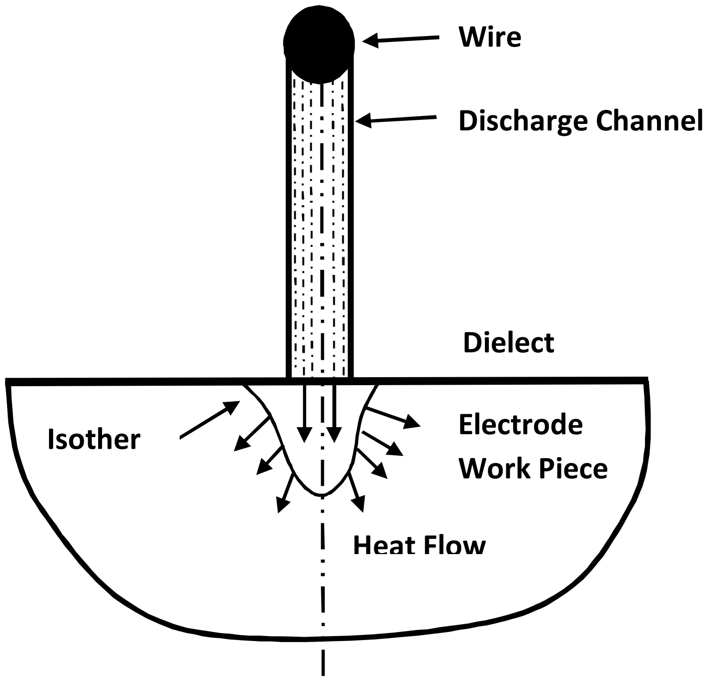


Fig.4 Spark channel configuration.

3.1.4 Initial condition:

At the start of the EDM process (t = 0), the workpiece is immersed in the electrolyte and the temperature of the whole domain is assumed to be at room temperature (T_0).

3.1.5 Boundary conditions

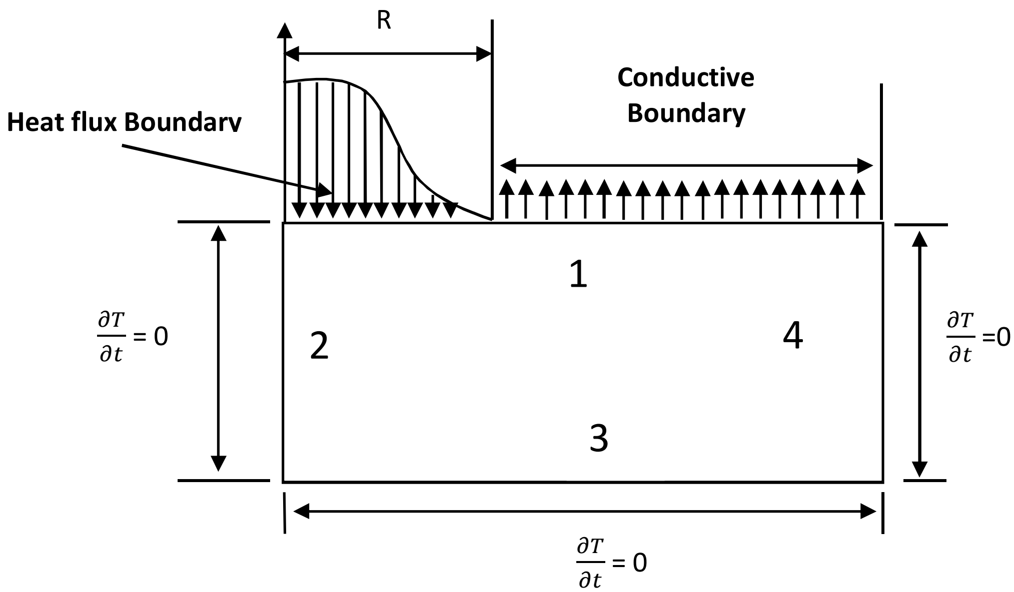


Fig. 5 An axisymmetric model for the EDM process simulation

The workpiece is axisymmetric about z-axis, and small half-plane is cut from the workpiece with negligible thickness. The considered workpiece domain is shown in Fig. 2. The heat flux for a single spark is applied on the surface 1 up to R (spark radius) using Gaussian distribution. On the remaining surface 1, the convection heat transfer takes place due to the cooling effect caused by the dielectric fluid. As the Surface 4 and 3 are far from the spark radius and also the spark has been made to strike for a very small amount, so no heat transfer conditions have been assumed on that surface. For surface 2, which is axisymmetric, the heat flux has been taken as zero.

1. For boundary surface 1

   Up to spark radius (R):

   $$K \frac{\partial T}{\partial z} = Q(r).$$

   Beyond Spark Radius R

   $$K \frac{\partial T}{\partial z} = h(T - T_0)$$

2. For boundary 4, 3, 2

   $$\frac{\partial T}{\partial z} = 0$$

Where, h is the heat transfer coefficient between the workpiece surface and dielectric, Q(r) heat flux, T_0 is the initial temperature which is room temperature and T is Temperature.

3.1.6 Shape of the domain

As the tool (wire) and the workpiece assumed to isotropic, therefore, the heat distribution would be Gaussian distribution in nature on the surface of workpiece as well as tool (wire).

3.1.7 Material properties:

The wire EDM is thermal process, and huge thermal energy is generated. And after that the workpiece temperature rise up to boiling temperature of the materials. In this work the variation of the materials properties with temperature are taken. The materials properties and chemical composition of Inconel 718, Titanium 15 and 5 Cr die steel, and are given in table 1, 2 and 3 respectively.

Chemical composition (wt.% of main alloying elements) of Inconel 718, Titanium 15 and 5 Cr die steel

Table 1: chemical composition of Titanium 15

Titanium 15							
Element	C	Fe	H	N	O	Ti	C
Content (%)	0.1	0.3	0.015	0.03	0.25	Bal	0.1

Table 2: chemical composition of Inconel 718

Inconel 718							
Element	Ni+Co	Cr	Fe	Nb+Ta	Mo	Ti	Al
Content (%)	50-55	17-21	Bal	4.45-5.5	2.8-3.3	0.65-1.15	0.2-0.8

Table 3: chemical composition of 5 Cr die steel

5 Cr die steel									
Element	Cr	Ni	C	Mn	Si	P	S	N	Mo
Content (%)	4-6	-	0.1	1	1	0.04	0.03	-	0.4-0.65

Table 4: chemical composition of 5 Cr die steel

Thermal properties and Mechanical Properties of Inconel 718	
Thermal Conductivity, K(W/mK)	11.4
Specific Heat, C(J/kg K)	435
Density, ρ (kg/m^3)	8190
Melting Temperature (K)	1609
Young's Modulus, E (GPa)	205
Poisson's Ratio	0.29

Table 5: chemical composition of Titanium 15

Thermal properties and Mechanical Properties of Titanium 15	
Thermal Conductivity, K(W/mK)	7.60
Specific Heat, C(J/kg K)	490
Density, ρ (kg/m^3)	4900
Melting Temperature (K)	1923
Young's Modulus, E (GPa)	115
Poisson's Ration	0.287 to 0.391

Table 6: chemical composition of 5 Cr die steel

Thermal properties and Mechanical Properties of 5 Cr die steel	
Thermal Conductivity, K(W/mK)	48.5
Specific Heat, C(J/kg K)	425
Density, ρ (kg/m^3)	8593
Melting Temperature (K)	2100
Young's Modulus, E (GPa)	208
Poisson's Ratio	0.30

3.1.8 Heat Flux due to the workpiece in a single spark

Most of the researchers [42, 43, 44] have considered had considered uniformly heat source in between a spark. In the present work, a Gaussian heat distribution is assumed. If it is assumed that total power of power of each pulse is to be used only single spark can be written as follows

$$Q_w(r) = \frac{4.45\ H_i V I}{\pi R^2} exp\left\{-4.5\ \left(\frac{r}{R}\right)^2\right\} \quad \text{.... (ii)}$$

Where r is the radial distance from the axis of the spark, R is the spark radius, V is the voltage and I is the current and H_i is heat input on workpiece.

3.1.9 Spark Radius

Spark radius is an important parameter in the thermal modeling of WEDM process. In practice, it is very difficult to measure experimentally, because spark radius very short pulse duration of in microseconds. According to Donald et al [47] the Spark Theory on a wire EDM is basically the same as that of the vertical EDM process. In wire EDM, the conductive materials can be machined with a series of electrical sparks, which are produced between an accurately positioned moving wire (electrode) and the workpiece. High frequency pulses of AC or DC is discharged from the wire (electrode) to the workpiece with a very small spark gap through an insulated dielectric fluid (distilled water).

3.1.10 Energy Distribution

Another parameter is Energy distribution is important in the thermal modeling analysis of WEDM process. The total spark's power gets divided into three parts, (i) a portion conducted away by the cathode, (ii) portion conducted away by the anode, and (iii) the rest being dissipated in the dielectric. Few experimental studies have been reported in literature to determine these fractions of heat.

3.2 Process of Thermal Modeling using ANSYS® software

The governing equation (Eq. 1) with boundary conditions to solve by FEM to predict the temperature distribution at the end of each transient heat transfer analysis. ANSYS™ 13.0, FEM software is used. A 2-D continuum of size 120×30 µm is considered for the analysis. Two-dimensional, 4 Node Quadrilateral Element (thermal solid plane 55) with element is 1µm is use for analysis. Nonlinear material properties, viz. temperature dependent thermal conductivity, were employed. After the modeling the work is expanded for Micro Wire EDM with the different parameter is given in the table, ANSYS Parametric Design is used to build the single-spark EDM model.

Objective:

The objective of this analysis is to find out the temperature distribution on the workpiece processed by micro wire EDM

Thermal Modeling steps are as follows:

- Create model geometry ($120\times 30\mu m$), it using PLANE 55, 4 Node Quadrilateral Element (thermal solid plane 55).
- Define the material properties and mesh size of 1 µm. temperature dependent thermal conductivity, density, heat capacity.
- Set the initial temperature as 25^o C (298^oK)
- Apply the boundary conditions and solve the solution
- Read the result and Plot the result for nodal solution.
- Finish.

3.3 Modeling of MRR of µ wire EDM

The thermal modeling has discussed above and it assume as a single spark. Actual material removal rate during WEDM process is governed by various factors such as ignition delays, high frequency of sparks, flushing efficiency, phase change of electrodes, dielectric medium, and random behavior of debris particles.

The nodes showing temperature more than melting temperature is selected and eliminated from the complete mesh of the work domain for further analysis. A typical crater cavity generated by this analysis. Calculate is done for single spark only the cavity volume is divided into the no. of the cylindrical size (fig. 5). The 2D model of the node boundary generated in ANSYS 13.0 to calculate the crater volume

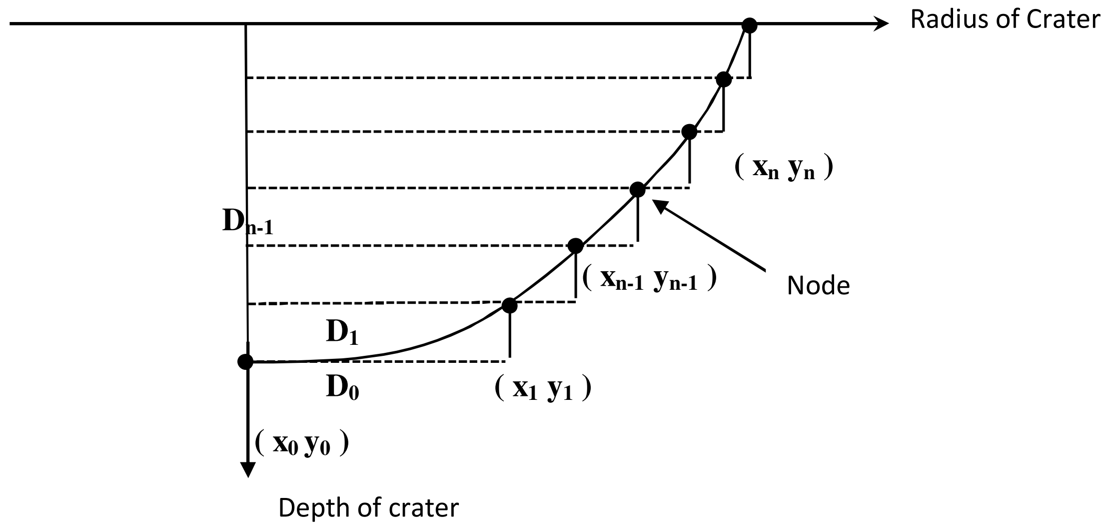


Fig 6 . Calculation of carater Volume

The carter volume C_{vol} (μm^3) is given by [50]

$$C_{vol} = \sum_{n=0}^{n-1} V_{disc} .. \qquad (iii)$$

Where volume of a disc, V_{disc} is given by [50]

$$V_{disc} = \pi \left(\frac{x_n + x_{n+1}}{2}\right)^2 (y_{n+1} - y_n).. \qquad \text{(iv)}$$

Where x and y are the coordinates of nodes and n is the no. of nodes

Eqs 2 and 3 is used for to calculate the crater volume generated by a single spark. As a result, in the present work, ideal MRR is calculated for only for selected condition that all sparks are equally distributed with 100% flushing.

$$MRR = \frac{60\ \times\ C_{vol}}{t_{on}\ + t_{off}} \ldots. \qquad (v)$$

Where C_{vol} is the material removed per discharge pulse, t_{on} is discharge duration and t_{off} is the discharge off time

3.3.1 MRR calculation for multi- discharge

For the multi discharge analysis [51]

$$\text{No. of pulse} = \frac{T_{machining}}{t_{on}+ t_{off}} .. \qquad \text{(vi)}$$

$$\text{MRR}_{Multi-discharge} = No\ of\ Pulse\ \times\ \text{MRR}_{single-discharge} .. \qquad \text{(vii)}$$

3.4 Measuring residual stress caused by Wire EDM

Residual stresses are self-acting stresses that exist in a body if thermal or mechanical loads are removed. They occur when a body is subjected to sharp temperature gradient caused by the temperature cycle at the surface and thermal contraction of re-solidified material on workpiece, with respect to plastic deformation, results of the formation of tensile residual stress [49]. Residual stress trend perhaps changed by the metallurgical alteration relating volumetric changes, Residual stresses cannot be measured using the standard displacement or strain-gage measurements since these methods only measure change in stress due to applied loads.

3.4.1 Causes of residual stresses

Residual stresses are generated during most manufacturing processes involving material deformation, heat treatment, machining or processing operations that transform the shape or change the properties of a material. They are originated from a number of sources and can be present in the unprocessed raw material, introduced during manufacturing or arise from in-service loading. It is possible classified the origin of residual stresses in the following way:

- Differential plastic flow;
- Differential cooling rates;
- Phase transformations with volume changes etc.

For example, the presences of tensile residual stresses in a part or structural element are generally harmful since they can contribute to, and are often the main cause of fatigue failure and stress corrosion cracking. Indeed, compressive residual stresses induced by different means in the (sub) surface layers of material are usually beneficial since they prevent origination and propagation of fatigue cracks, and increase wear and corrosion resistance. Examples of operations that produce harmful tensile stresses are thermal, machining, etc.

The temperature gradients that happen during EDM (in space and time) result in extreme no homogeneities in the local thermal expansion of workpiece material (strain) which lead to high thermal stresses. The transient temperature distribution in the workpiece, found by solving the heat conduction equation [Eq. (1)] along with the boundary and initial conditions, is used as input for the calculation of thermal stresses Vinod Yadav et al [58]. A coupled thermal-structural finite element analysis will also be resented, with results to show how the thermal action of the micro-EDM process affects the surface integrity of machined workpiece Xiaolin Chen et al [52]. After that it is converted in the micro wire EDM for analysis. The Spark Theory on a wire EDM is basically the same as that of the vertical EDM process Donald et al [47].

3.5 Coupled thermal-structural finite element simulation

The surface quality is very essential to control during machining process. Material removed by the thermal discharge action of the micro machining induced the residual stress and affects the surface integrity. The surface cracks comes out in small manner and stress corrosion cracking may appear as result, which will reduced the fatigue life of the component

To find the induced stress in the workpiece, using Transient analysis profile due to a spark discharge has to be determined. A sequentially coupled thermal-structural analysis is performed in this study using the commercial FEM package ANSYS 13.0. An axisymmetric model is employed with element type ‘Plane 55’ for the thermal analysis and ‘Plane 182’ for the structural analysis.

5.1 Boundary condition for the structure analysis

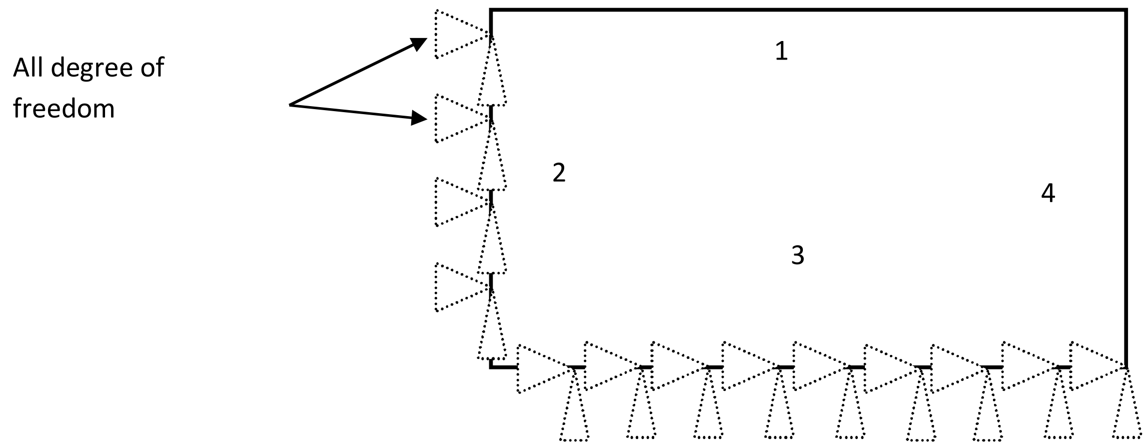


Fig 7: Boundary condition for structure model

For structure analysis give the boundary condition as displacement at surface boundary 2 and 3 is 0 for all degree of freedom as shown in the fig 7.

3.5.2 Coupled thermal-structural modeling procedure using ANSYS software.

The model is to be developed by using ANSYS 13.0 multi-physics, uses the finite-element method to solve the underlying governing equations and the associated problem-specific boundary conditions.

For the micro analysis taking the geometry taken as 120×30 µm with the element size 1 µm.

Objective:

The objective of this analysis is to find out the residual stress distribution on the workpiece processed by micro wire EDM

Coupled thermal-structural modeling procedure steps are as follows:

- Create model geometry ($120\times 30\mu m$), Choice of element PLANE 55, 4 Node Quadrilateral Element (thermal solid plane 55).
- Define the material properties and mesh size of 1 µm. temperature dependent thermal conductivity, density, heat capacity.
- Apply load as per the boundary conditions for thermal
- Set the initial temperature as $T_0 = 25^o$ C (298^oK)
- Solve by Current LS
- Change the loading title and loading as required for the next solution. Loads and constraints which are not changed or removed remain in the next solution step.
- Apply the boundary conditions for structure analysis
- Transfer the thermal load conditions into the structure.
- Read result and plot.
- Finish.

Chapter 4

- **Optimization Techniques**
    - Overview of Fuzzy Inference Process.

Optimization Techniques

4.1 Designing Fuzzy Inference Systems Method:

Fuzzy inference systems (FIS) are one of the most popular applications of fuzzy logic and fuzzy sets theory. They can be helpful to attain classification tasks, offline process simulation and analysis, online decision support tools and process control.

Fuzzy inference systems have been successfully useful in fields such as automatic control, data classification, decision analysis, skilled systems, and computer vision. Because of its multidisciplinary environment, fuzzy inference systems are related with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply fuzzy systems

4.1.1 Overview of Fuzzy Inference Process

This section defines the fuzzy inference process and uses the example of the two-input, one-output, three-rule tipping problem. Information runs from left to right, from two inputs to a single output. The parallel environment of the rules is one of the more important features of fuzzy logic systems. Instead of sharp switching between modes based on breakpoints, logic flows smoothly from areas where the system's behavior is controlled by either one rule or another.

Fuzzy inference process contains of five parts: fuzzification of the input variables, application of the fuzzy operator (AND or OR) in the antecedent, suggestion from the antecedent to the resultant, aggregation of the consequents across the rules, and defuzzification. These sometimes hidden and odd names have very specific meanings that are defined in the following steps.

Step 1. Fuzzify Inputs

The first step is to take the inputs and determine the degree to which they belong to each of the proper fuzzy sets via membership functions. In Fuzzy Logic Toolbox software, the input is always a short numerical value limited to the universe of discourse of the input variable (in this case the interval between 0 and 10) and the output is a fuzzy degree of membership in the qualifying language set (always the interval between 0 and 1). Fuzzification of the input amounts to either a table lookup or a function estimation.

Step 2. Apply Fuzzy Operator

After the inputs are fuzzified, we know the degree to which each part of the originator is satisfied for each rule. If the originator of a given rule has more than one part, the fuzzy operator is applied to get one number that represents the result of the originator for that rule. This number is then applied to the output function. The input to the fuzzy operator is two or more belonging values from fuzzified input variables. The output is a single truth value.

Step 3. Apply Implication Method

Before applying the implication method, we must decide the rule's weight. Every rule has a weight (a number between 0 and 1), which is applied to the number given by the originator. Generally, this weight is 1 (as it is for this example) and thus has no influence at all on the effect process. From time to time we may want to weight one rule approximate to the others by changing its weight value to something other than 1.

Step 4. Aggregate All Outputs

Because choices are based on the testing of all of the rules in a FIS, the rules must be mutual in some manner in order to make a choice. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are joined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the fifth and final step, defuzzification. The input of the aggregation process is the list of shortened output functions returned by the suggestion process for each rule. The output of the aggregation process is one fuzzy set for each output variable.

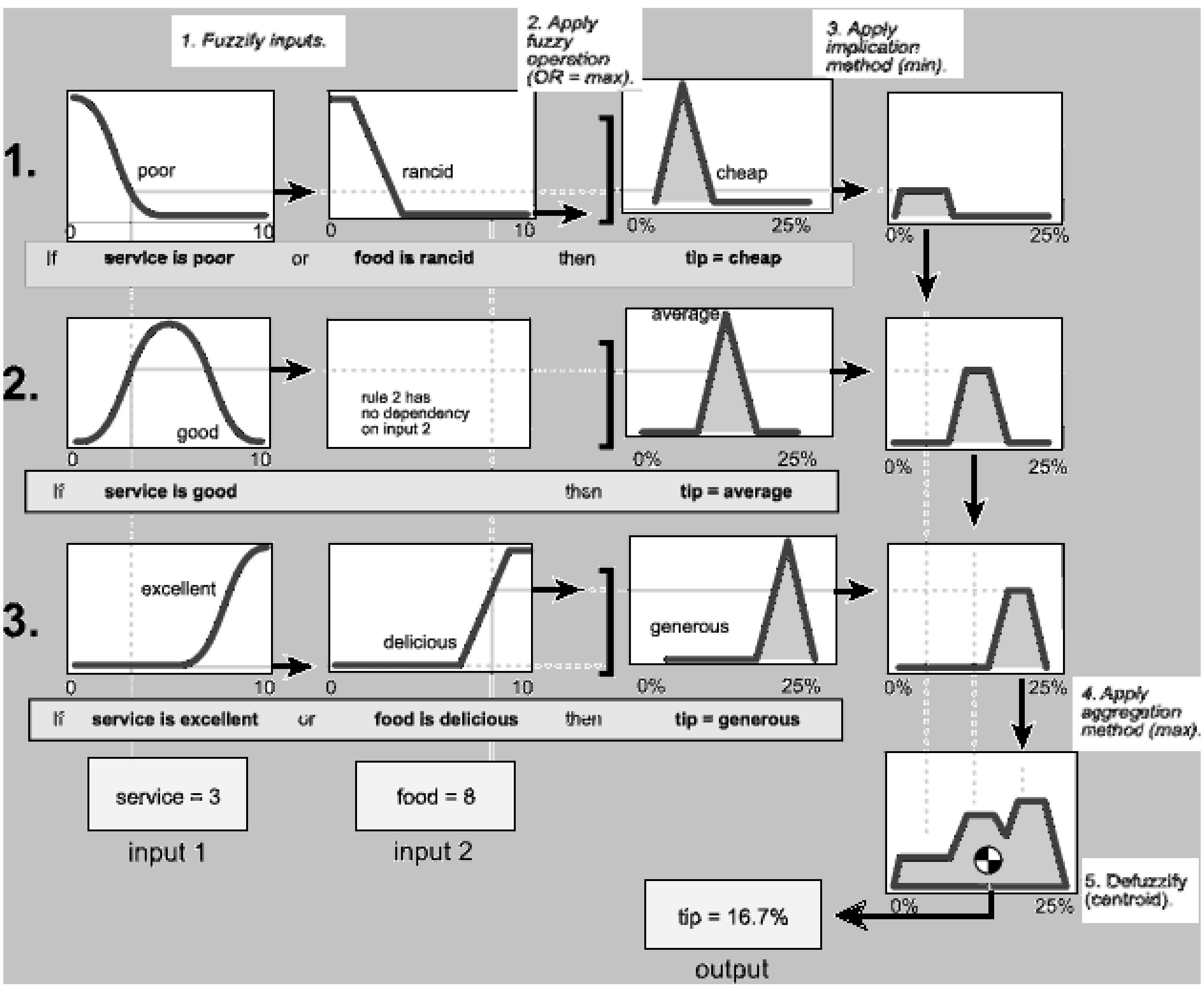


Fig. 8 single fuzzy set whose membership function assigns a weighting for every output [59]

Step 5. Defuzzify

The input for the defuzzification process is a fuzzy set and the output is a single no. As much as fuzziness assistances the rule evaluation during the in-between steps, the final preferred output for each variable is generally a single no. However, the total of a fuzzy set includes a range of output values, and so must be defuzzified in order to decide a single output value from the set.

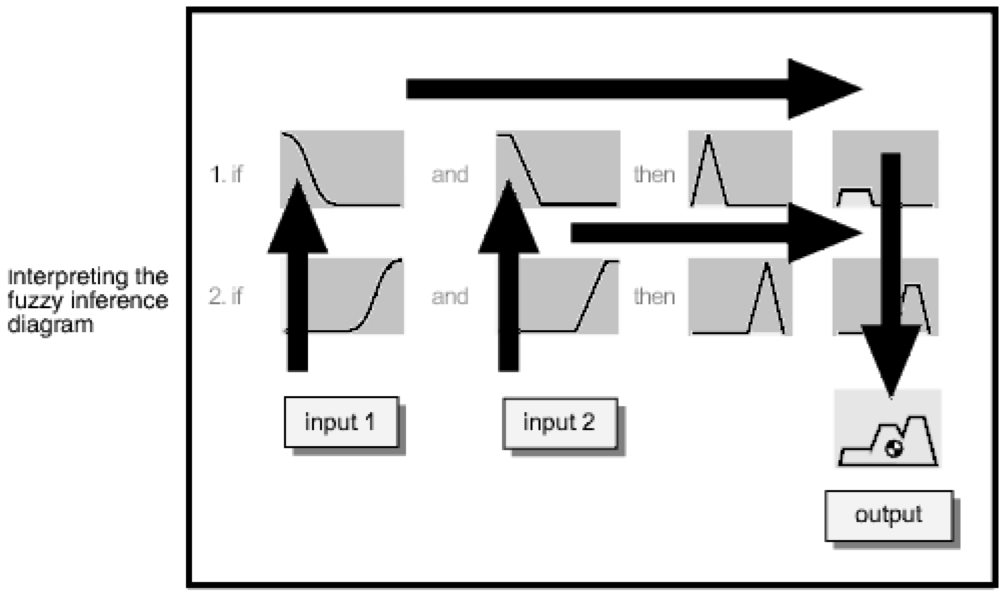


Fig. 9 Defuzzify method[59]

For the experimental work our main responses are:

- Kerf width
- Burr size
- MRR

For optimization of FEA model our main responses are:

- MRR
- Residual stress

Fig. 10 wire EDM machine (ECOCUT) at CTTC, Bhubneswar.

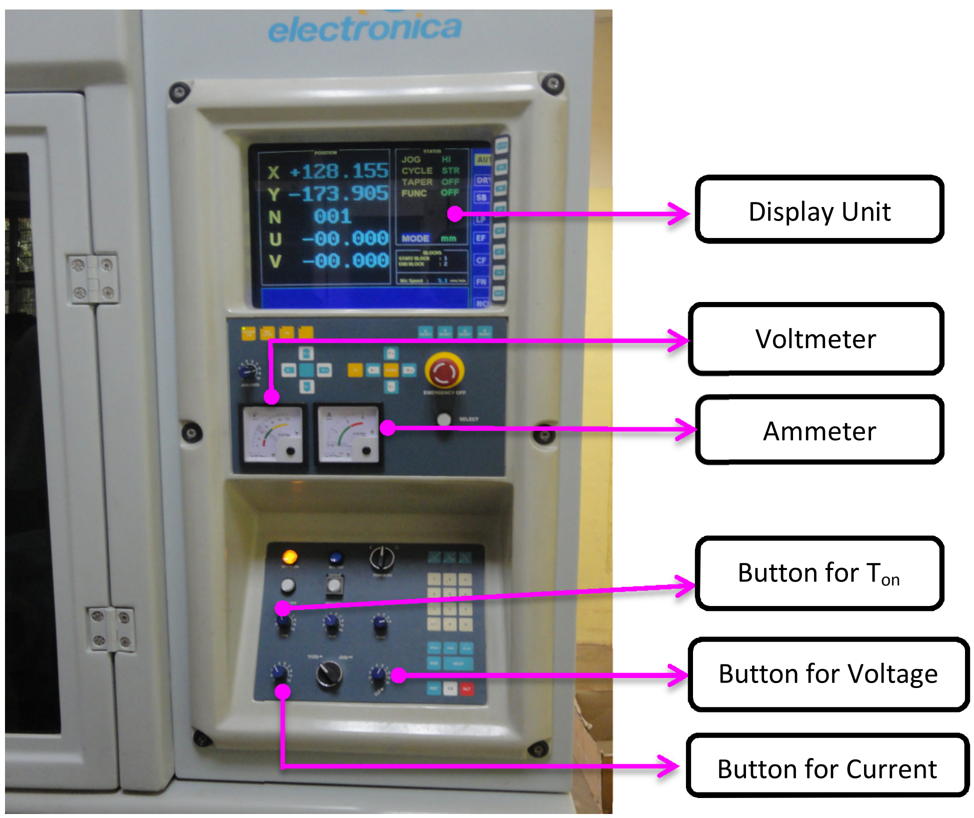


Fig. 11 : Controlling units

Table 7 Specifications of wire cut EDM

Dielectric	Distilled water
Maximum workpiece size	400 x 500 x 200 mm
Maximum travel	250 x 350 x 200mm
Manufacture	Electronica

Table 8 Machining parameters set-up (constant parameters)

Parameter	Setting Value
Main Power Supply Voltage, V (Volt)	415V, 3 phase
Servo Speed, SF (mm/min) At no load	normal
Wire Tension, WT (g)	2
Wire Speed, WS (mm/min)	10
Flushing Pressure, FP (bar)	1
Wire diameter (mm)	0.25
Polarity	Workpiece : Positive
Wire Electrode	Negative
Dielectric Fluid	Distilled water
Wire material	Brass wire

Experimental Details

- As per the taguchi quality design model L_4 orthogonal array table was arbitrarily chosen to study optimization process. The experimental design has 2 level and 3 factors.
- The process considerations have been optimized by Grey based Taguchi method.
- Experiments have been performed on ECOCUT.
- The dimension of cutting has to measure by using SEM image.
- The experimental design has been done in L_9 orthogonal array for modeling of micro wire EDM process.

Three response parameter were chosen for measured.

- Voltage
- Current.
- T_{on}

Table 9 Process parameters used for experiment

Parameters	Units	Value
Voltage	V	4, 8
Current	A	5, 7
Spark time (T_{on})	µs	2, 5

Table 10 Taguchi's L4 orthogonal array

S. No.	Voltage (V)	Current (A)	Ton (µs)
1	4	5	2
2	4	7	5
3	8	5	5
4	8	7	2

Process parameters used for modeling the micro cut wire EDM process has been shown in Table 9. For the optimization of ANSYS model parameter setting has been shown in Table 11.

Table 11 Process parameters used for modeling (Micro wire EDM)

PARAMETERS	Micro EDM (LEVELS)		
Voltage	20V	25V	30V
Current	2A	4A	6A
Heat input to the workpiece	0.09	0.16	0.20
Spark radius	5µm		
Pulse-on time	2µs		
Pulse-off time	100µs		

Table 12 Taguchi L9 Array of process parameters for Micro wire EDM

S. No.	VOLTAGE	CURRENT	HEAT INPUT
1	20	2	0.09
2	20	4	0.16
3	20	6	0.20
4	25	2	0.16
5	25	4	0.20
6	25	6	0.09
7	30	2	0.20
8	30	4	0.09
9	30	6	0.16

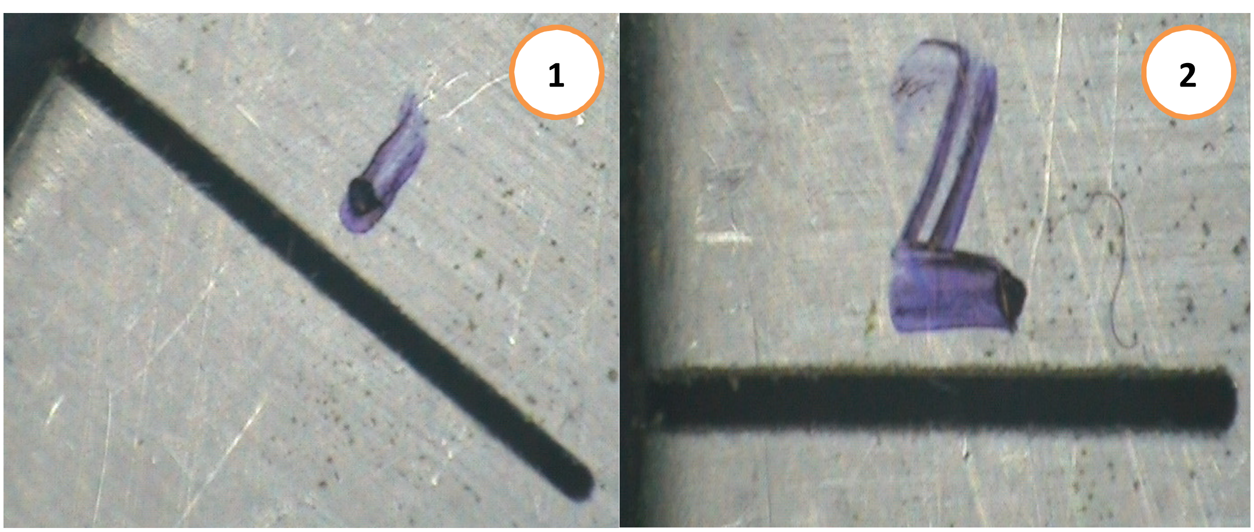
Chapter 5

- **Results and discussions**
- ANSYS model confirmation
- Thermal modeling of micro wire EDM for single spark
- MRR modelling of micro wire EDM for single discharge
- Residual Stress modelling of micro wire EDM for single discharge

5.1. Optimization of micro wire EDM

Four kerfs were cut according to design shown in Table 5 with process parameter setting as shown in Table 4. From the four kerf one can see the white colors disturbances around the cut area produced and that white colored disturbance is nothing but the hard layer which is called as the re-formed layer which always made around the micro wire EDMed cut. Re-formed layer is defined as a layer forms on the work material surface defined as a re-formed layer after solidification. This is formed due to sparks whose thermal energy melts the metal and then that melted metal undergoes rapid quenching to form re-form layer.

The main responses in present analysis are kerf width, burr size and MRR. The optimization criteria for all the response are Lower-the-Better.



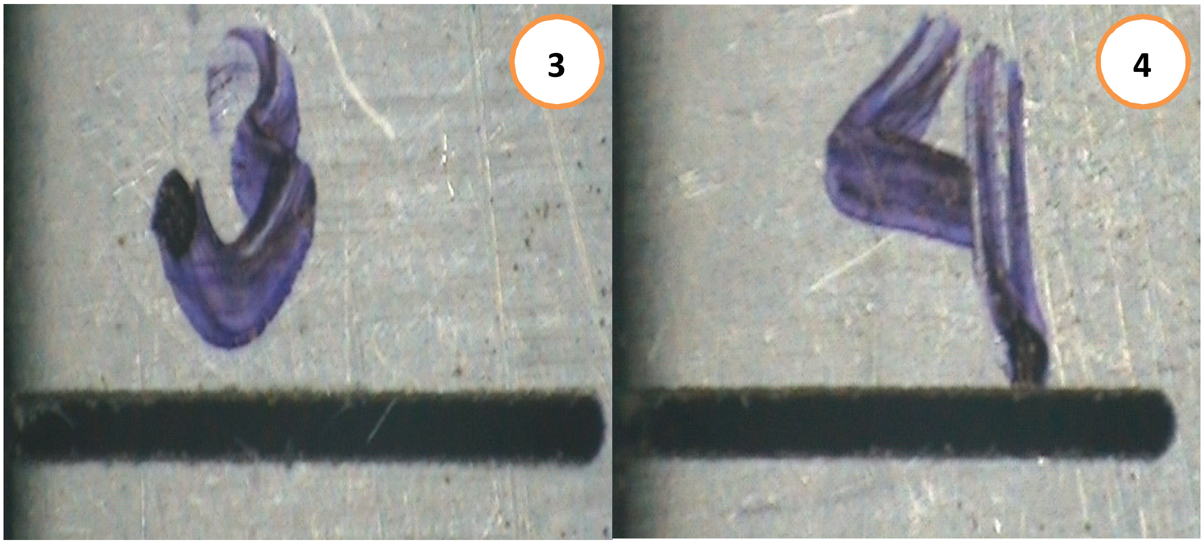


Fig. 12 workpiece after machining on Inconel 718 with different parameter settings

Fig. 13 wire cutting process during the experiment

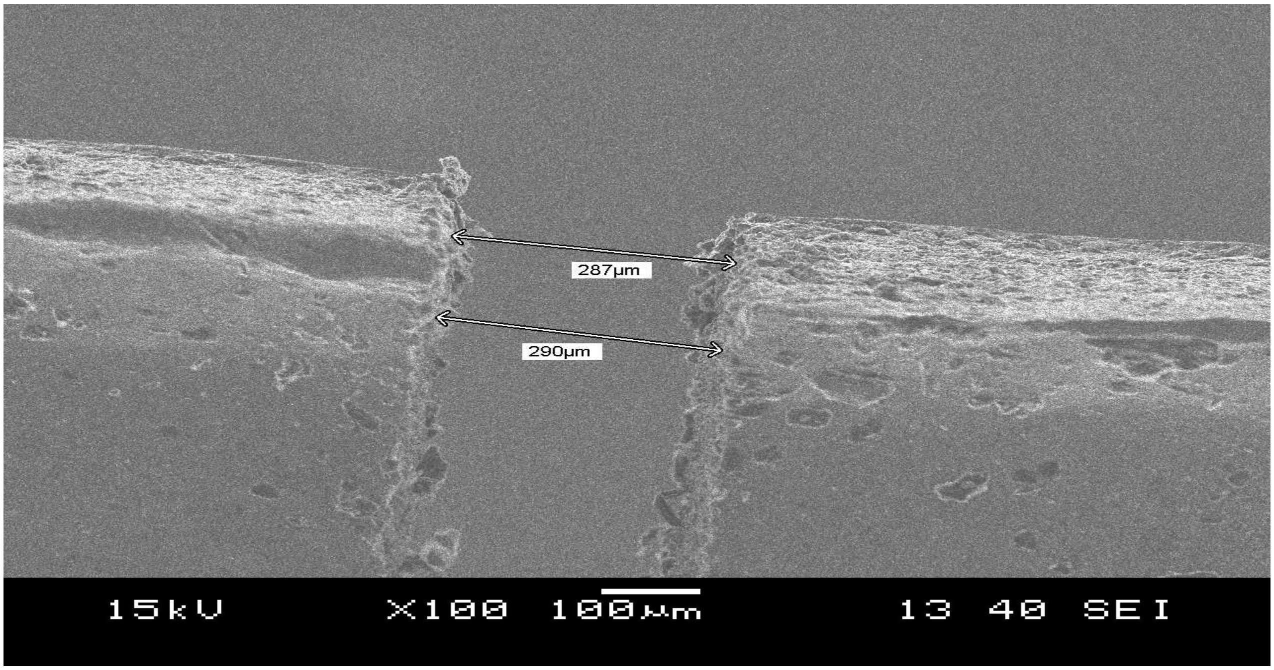


Fig. 14 SEM image of micro cut at V = 4V, I= 5A and Ton = 2μs

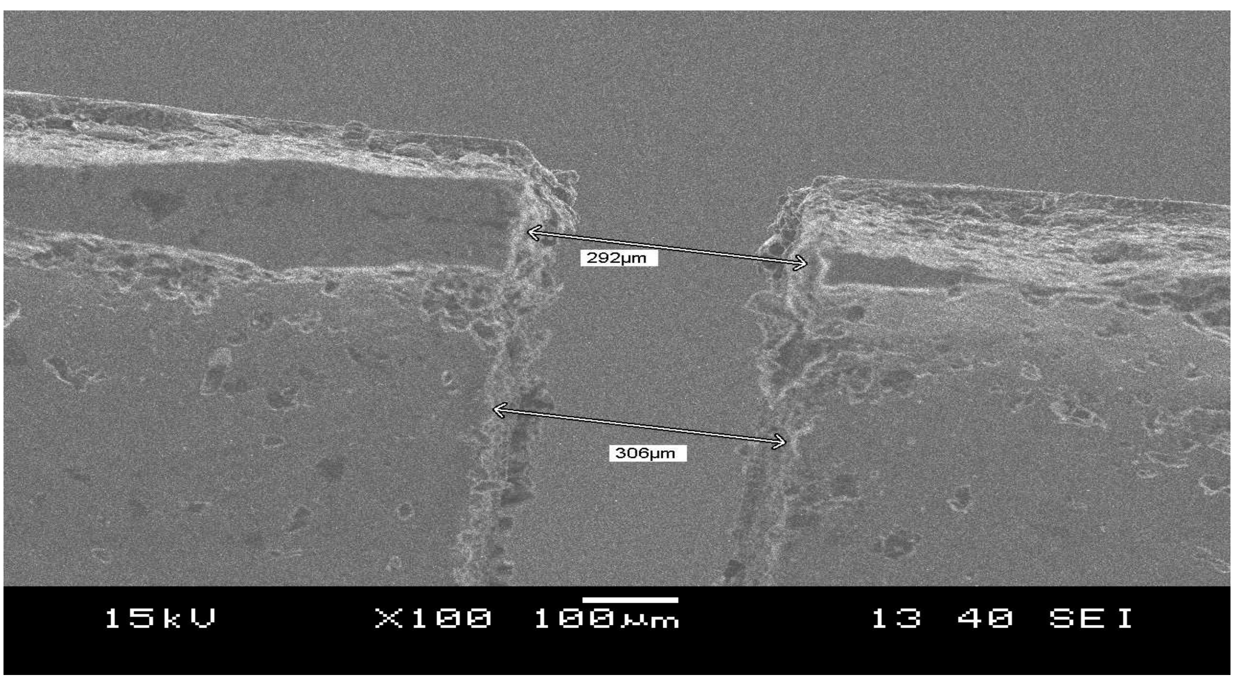


Fig. 15 SEM image of micro cut at V = 4V, I= 7A and Ton = 5μs

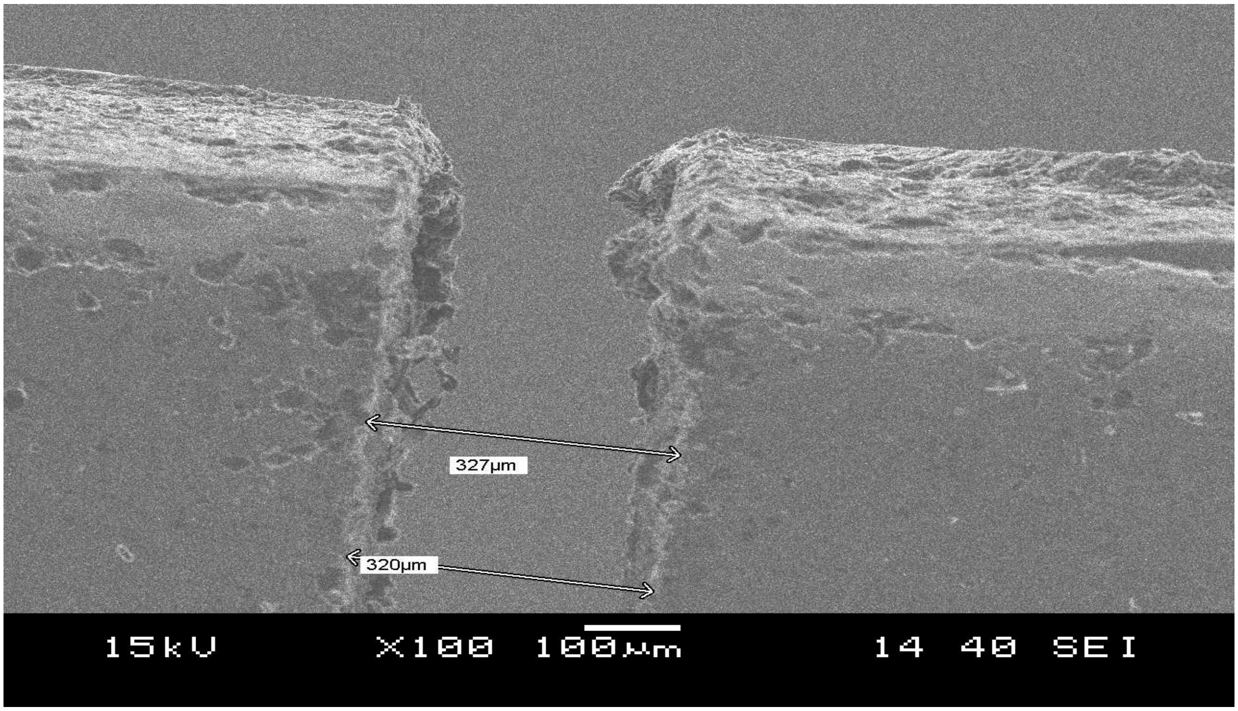


Fig. 16 SEM image of micro cut at V = 8V, I= 5A and Ton = 5μs

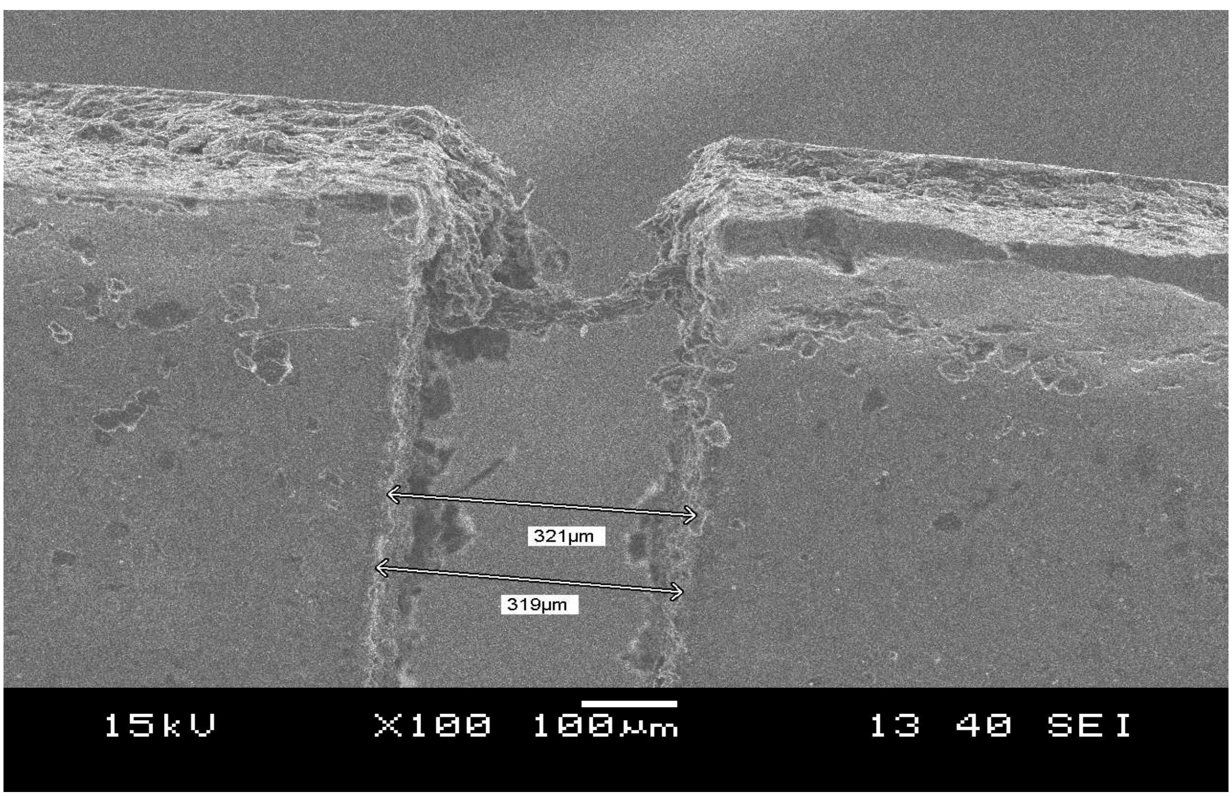


Fig. 17 SEM image of micro cut at V = 8V, I= 7A and Ton = 2μs

Table 13 Designing Fuzzy Inference Systems

S. No.	Cutting Speed (mm/min)	Kerf Width (mm)	Burr size (mm)	MRR (mm^3/min) x 10^{-4} Experimental value
1	5.1	0.287	0.1625	25.08
2	5.0	0.300	0.28	8.28
3	5.4	0.327	0.33	0.154
4	3.6	0.320	0.10	8.70

Table 14 Comparing the MRR, ANSYS Value Vs Experimental value

MRR (mm^3/min) x 10^{-4} Predicted value (ANSYS)	MRR (mm^3/min) x 10^{-4} Experimental value	Error (%)
31.25	25.08	19.74
11.05	8.28	25.06
0.197	0.154	21.83
11.536	8.70	24.6

Table 15 Fuzzy Inference Systems of each performance characteristics

VOLTAGE	CURRENT	Ton	MPCI	SNRA1	PSNRA1
4	5	2	0.780	-2.1581	2.22001
4	7	5	0.342	-9.3195	
8	5	5	0.080	-21.9382	
8	7	2	0.500	-6.0206	

Table 16 Response table (mean) for Fuzzy Inference Systems

VOLTAGE	CURRENT	Ton	MPCI	SNRA1	PSNRA1
4	5	2	0.780	-2.1581	2.22001
4	7	5	0.342	-9.3195	
8	5	5	0.080	-21.9382	
8	7	2	0.500	-6.0206	

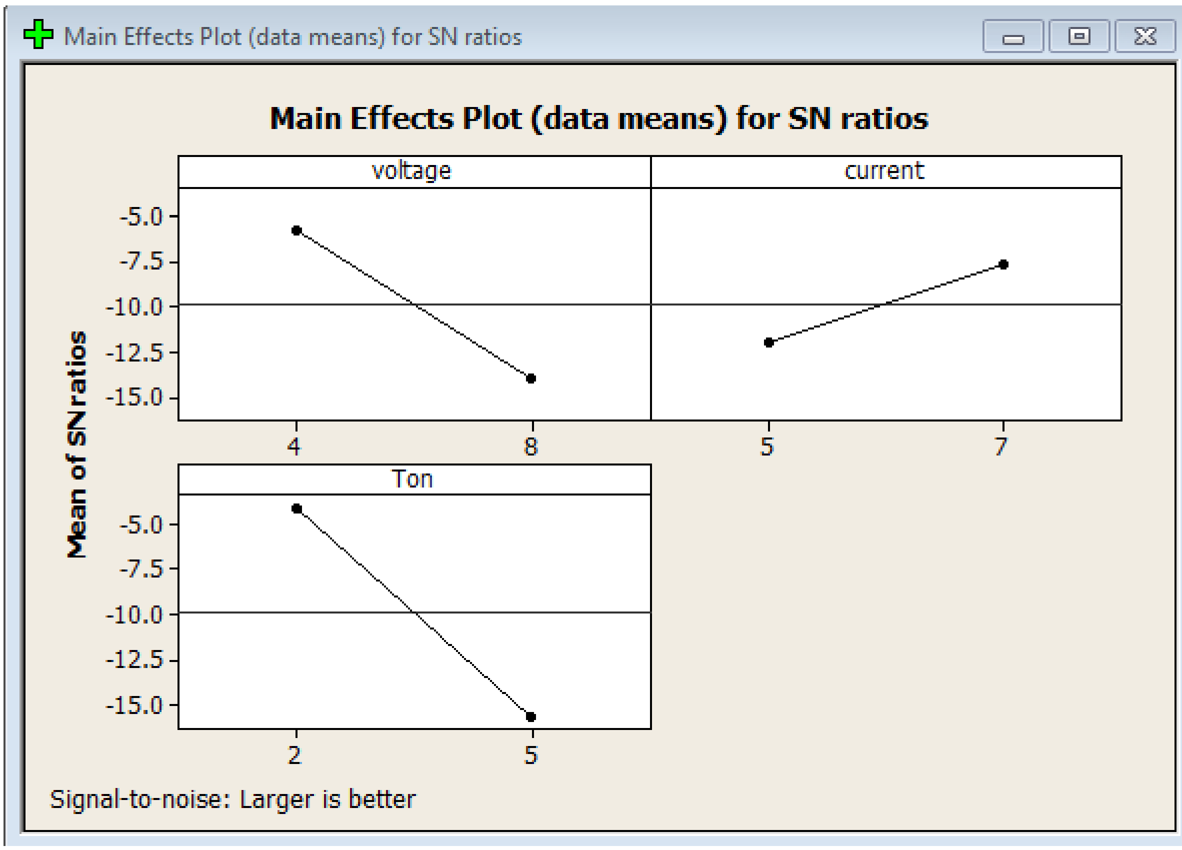


Fig. 18 Main effect plots

5.2 ANSYS model confirmation

In this section we have firstly make a model of EDM process for AISID2 die steel with parameter setting as given in Table 17 and workpiece dimension is $625 \times 625\ \mu m$. Later the value has been compared with H.K. Kansal et al Fig. 17 shows the plot for EDM process done for the AISID2 die steel. As element size is 20 μm (shown in Fig. 19), so we are getting the final temperature shown in Fig. 20, is 3149K,which is approximately same as given by H.K. Kansal [12]. So we can say that we are proceeding in right way. Further in the analysis the EDM problem is extended to the micro WEDM. For micro EDM the parameter setting is given in Table 17

Table 17 EDM process parameters

Parameters	Units	Value
Discharge voltage	V	30
Current	A	3.5
Percentage of heat input to the workpiece	0.15	
Spark radius	μm	120
Pulse-on time	μs	100
Heat transfer coefficient	W/m^2K	10,000

Table 18 Thermal properties and Mechanical Properties of AISID2 die steel

Thermal and Mechanical Properties of AISID2 die steel	
Thermal Conductivity, K(W/mK)	29.0
Specific Heat, C(J/kg K)	413
Density, ρ (kg/m^3)	7700
Melting Temperature (K)	1984
Young’s Modulus, E (GPa)	208
Poisson’s Ration	0.30

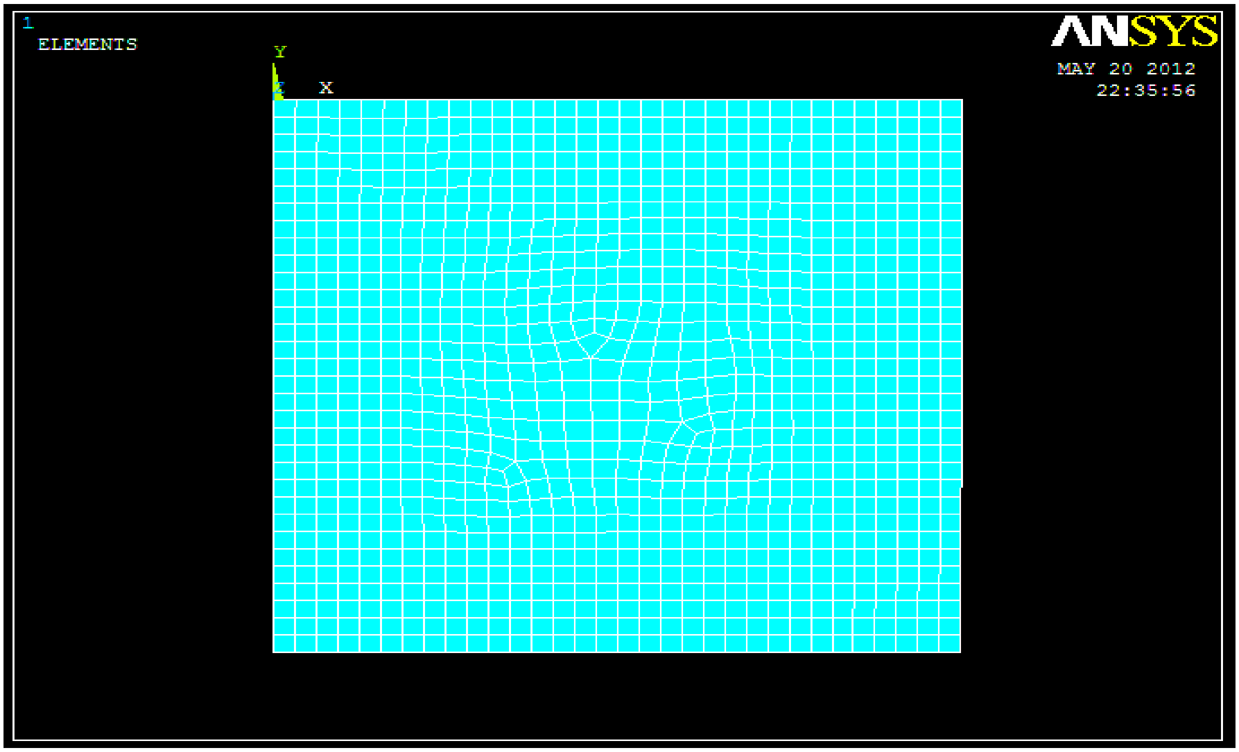


Fig. 19: Two-dimensional view of the meshed model with element size of 20µm

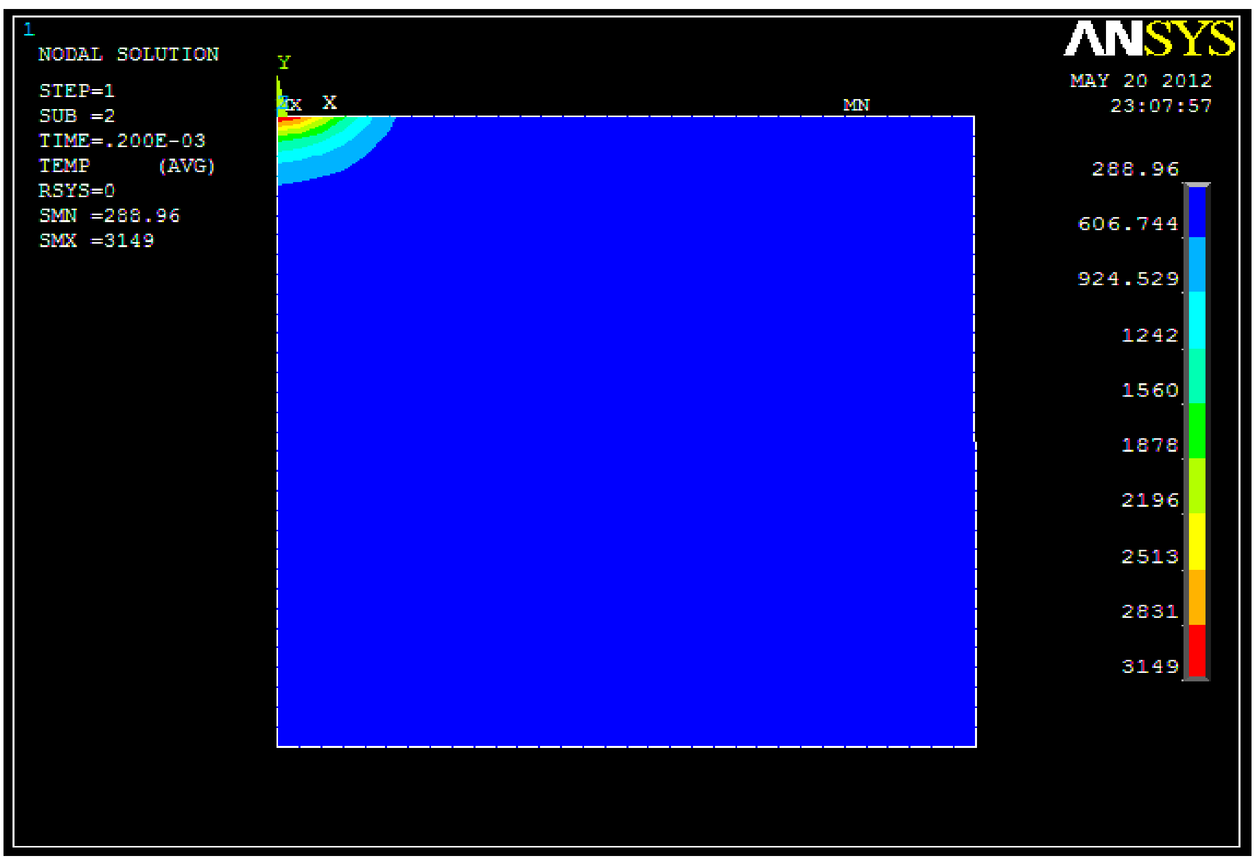


Fig. 20: Temperature isotherms for single spark of EDM process.

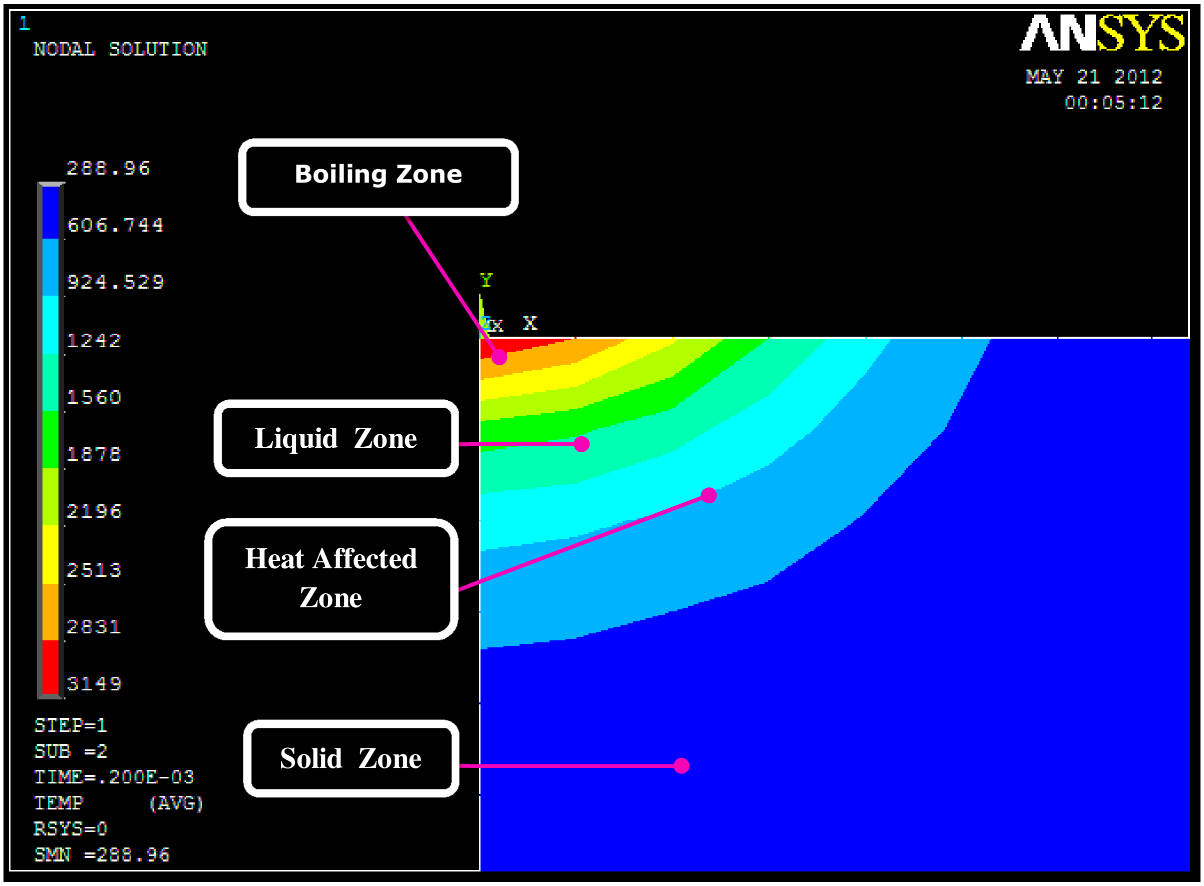


Fig. 21 : For interpretation of the references to colour in this figure

5.3 Thermal modeling of micro wire EDM for single spark

After the varying the result of thermal model for EDM process, now analysis the different process parameter from the table , and analysis the predict model.

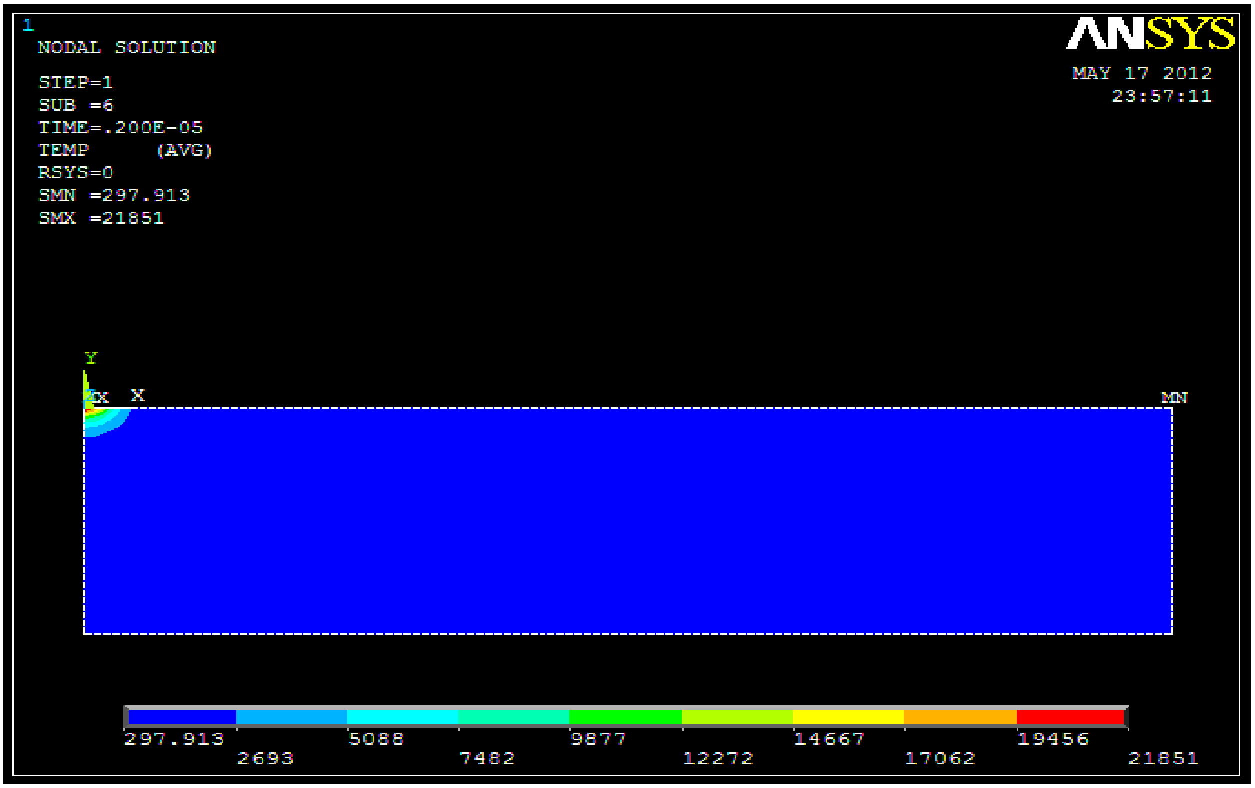


Fig. 22 Temperature distribution in Inconel 718 with V=20V, I=2.0A and P=0.09

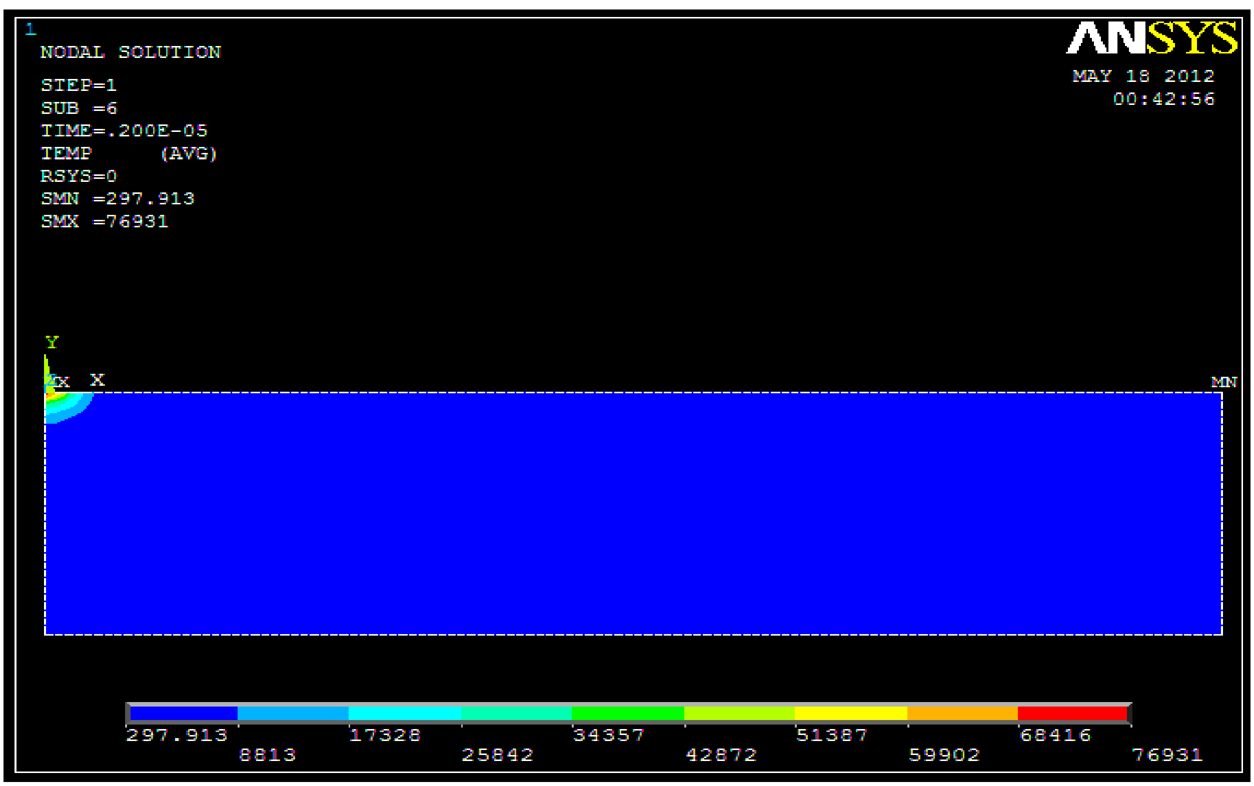


Fig. 23 Temperature distribution in Inconel 718 with V=20V, I=4A and P=0.16

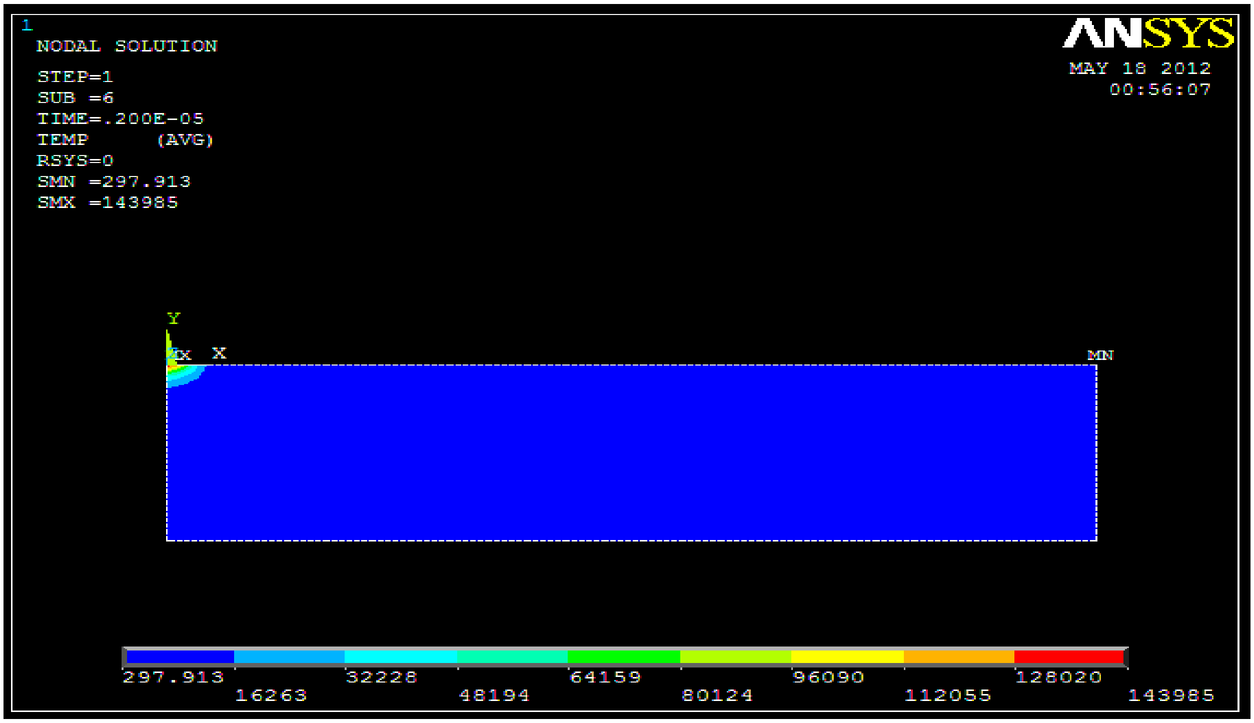


Fig. 23 Temperature distribution in Inconel 718 with V=20V, I=6A and P=0.20

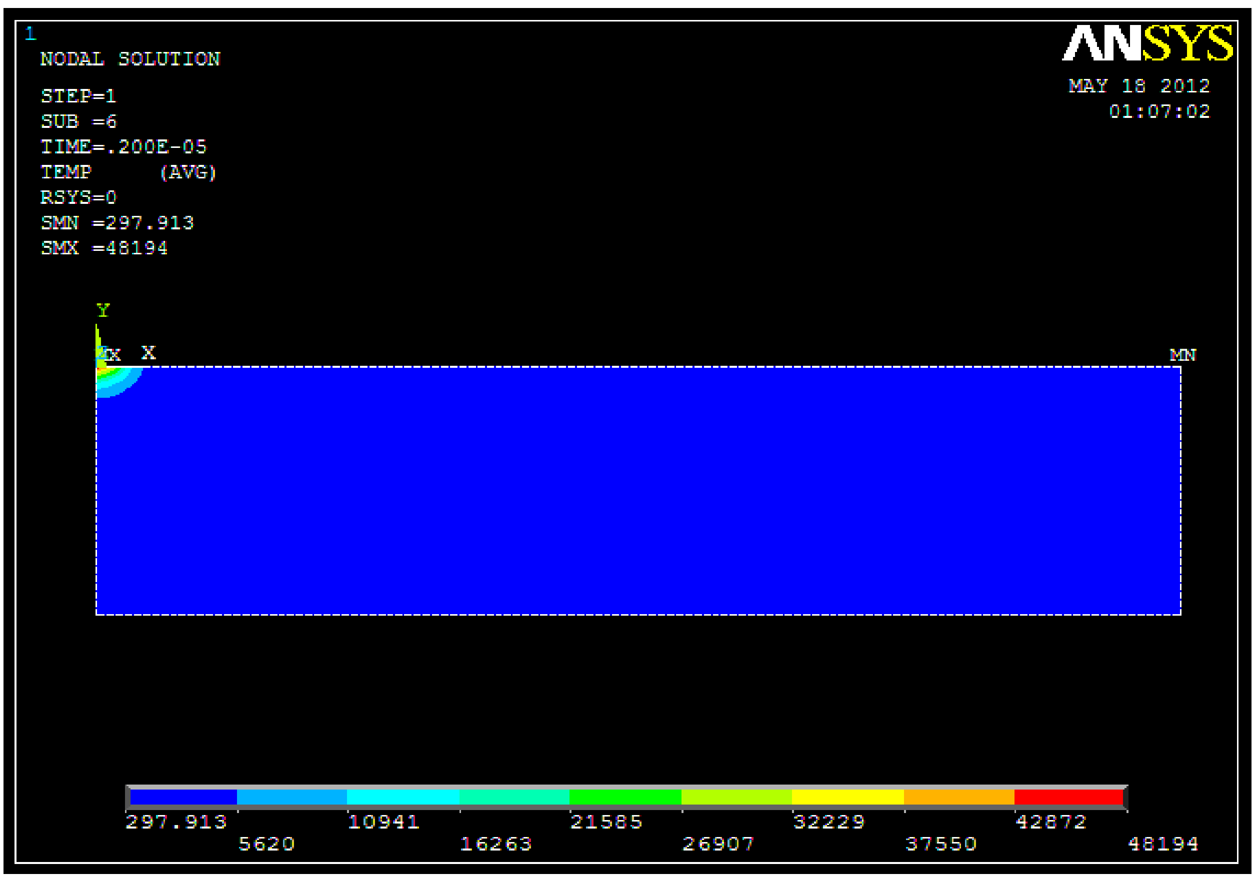


Fig. 25 Temperature distribution in Inconel 718 with V=25V, I=2A and P=0.16

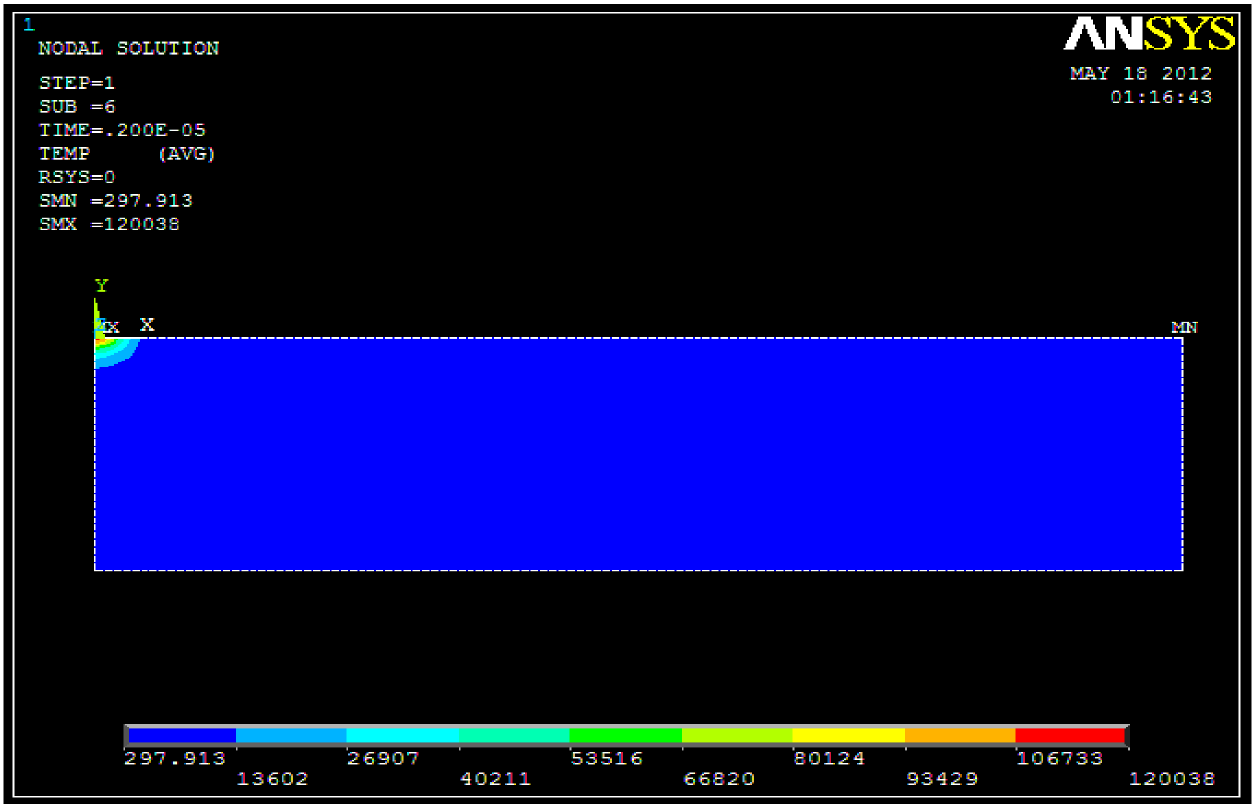


Fig. 26 Temperature distribution in Inconel 718 with V=25V, I=4A and P=0.20

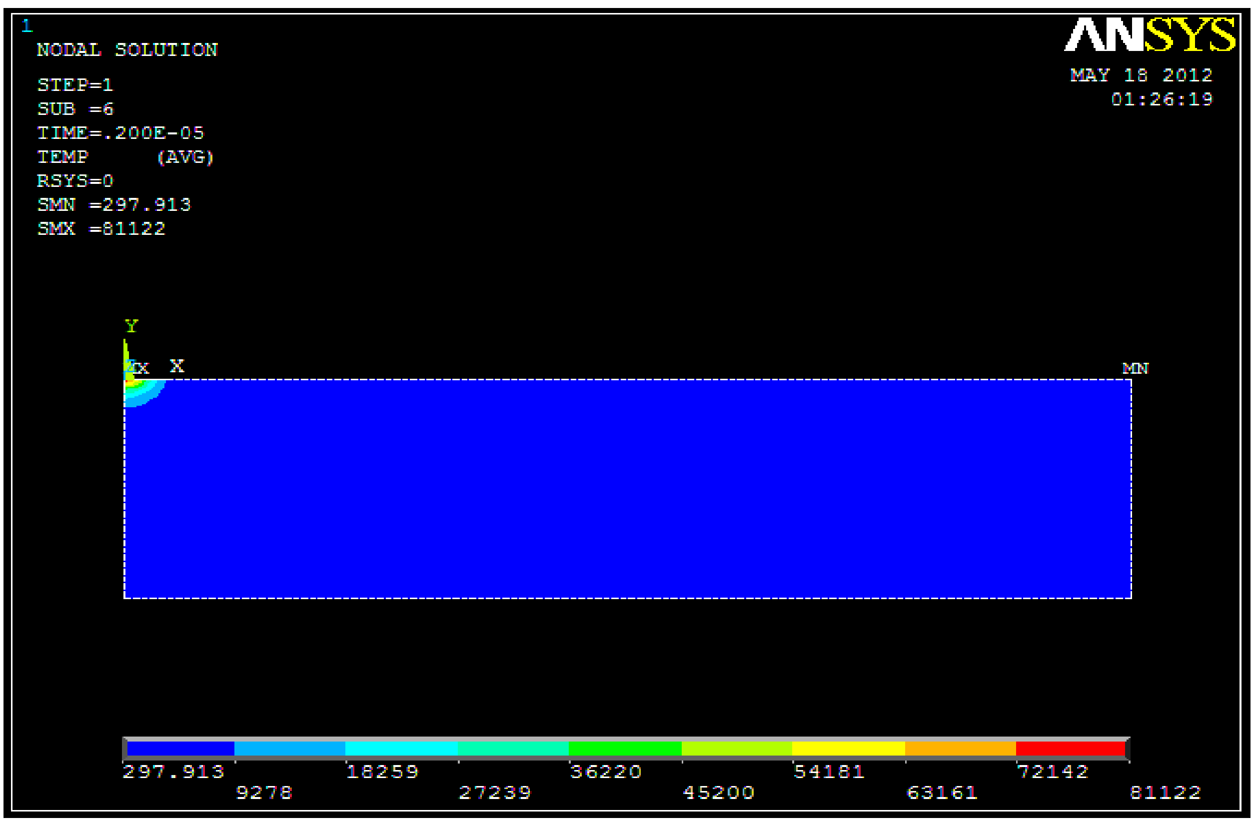


Fig. 27 Temperature distribution in Inconel 718 with V=25V, I=6A and P=0.09

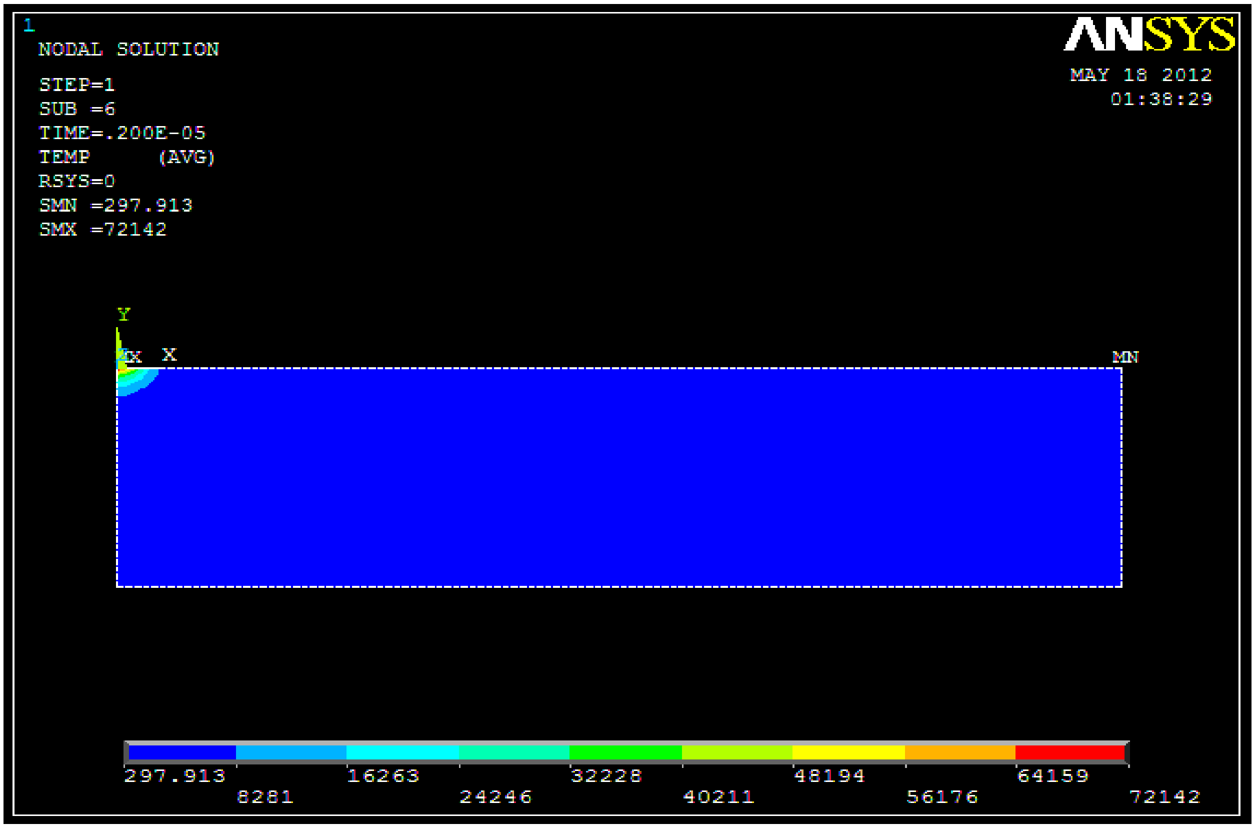


Fig. 28 Temperature distribution in Inconel 718 with V=30V, I=2A and P=0.20

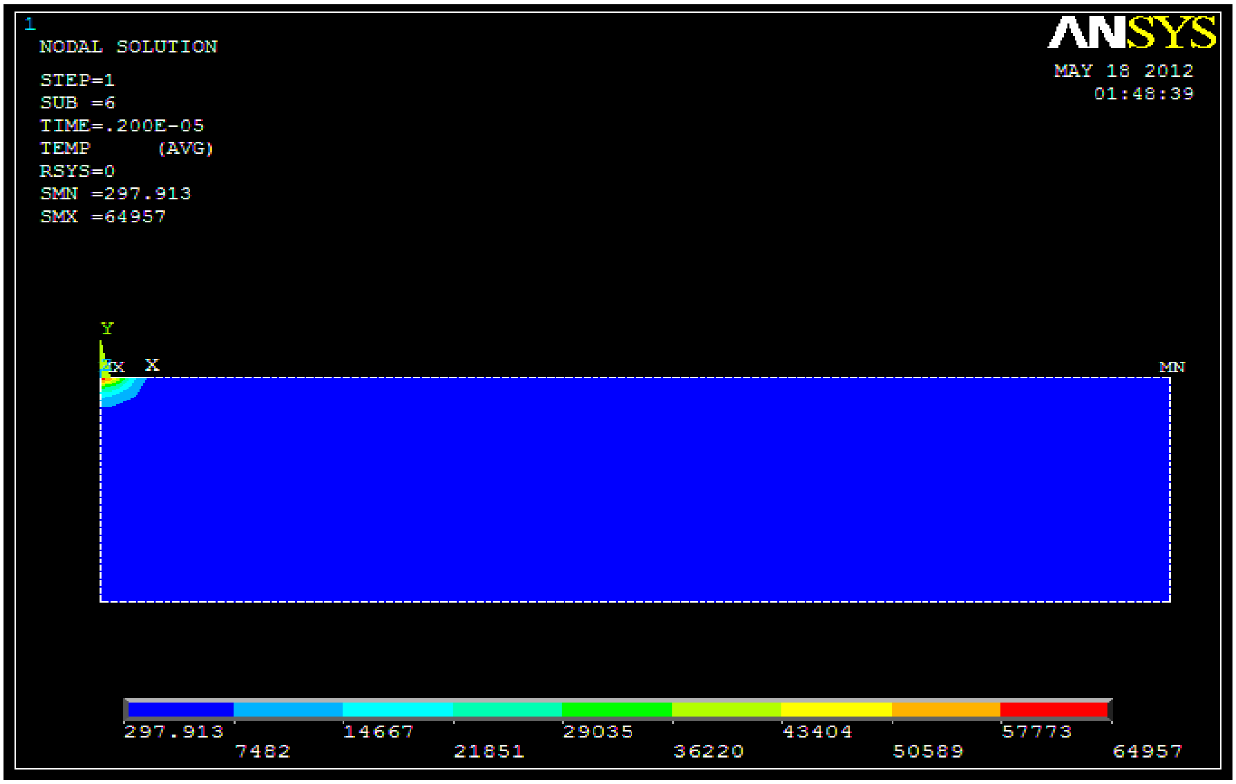


Fig. 29 Temperature distribution in Inconel 718 with V=30V, I=4A and P=0.09

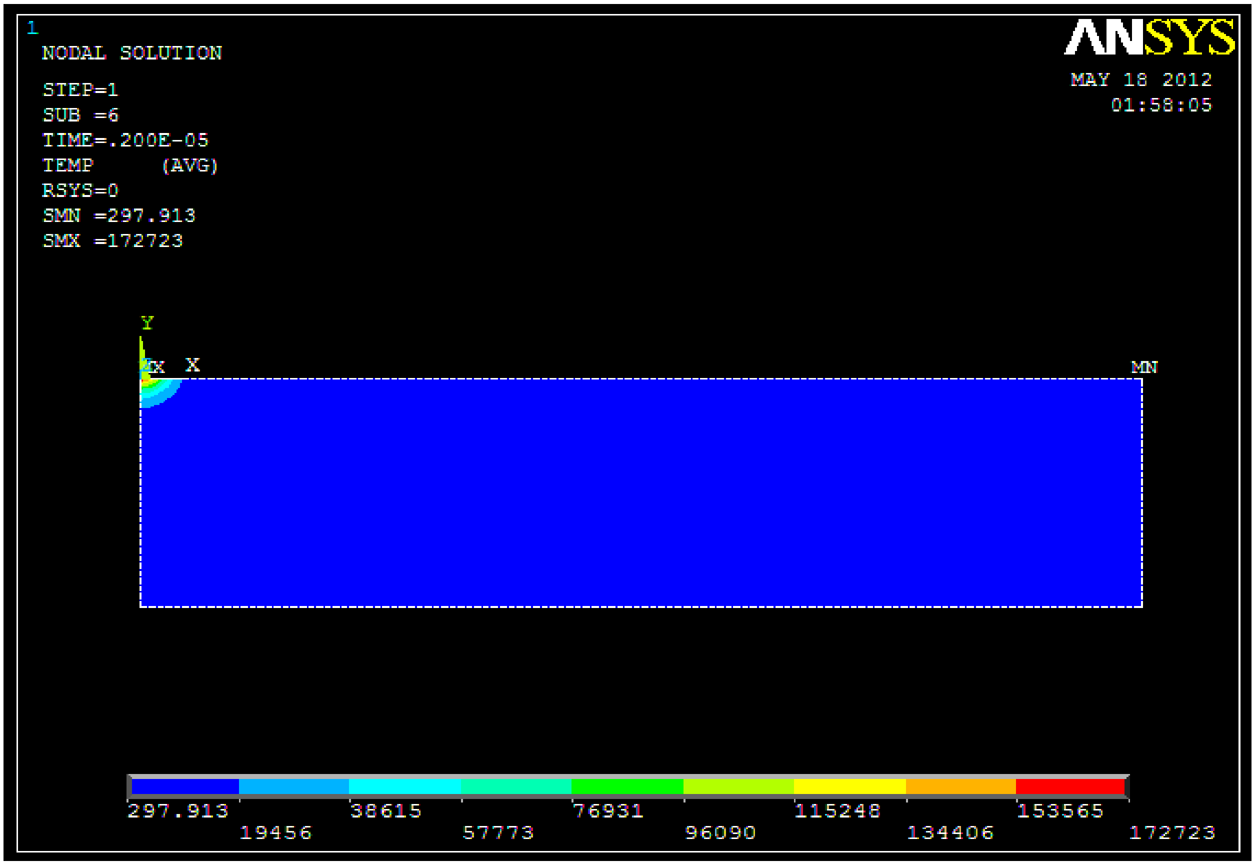


Fig. 30 Temperature distribution in Inconel 718 with V=30V, I=6A and P=0.16

5.4 MRR modelling of micro wire EDM for single discharge

After the getting the thermal modeling result for single spark, we go through the analysis the calculating the MRR. This result gets from the thermal model those temperatures above the melting point, which has to kill that element, using the kill/birth option

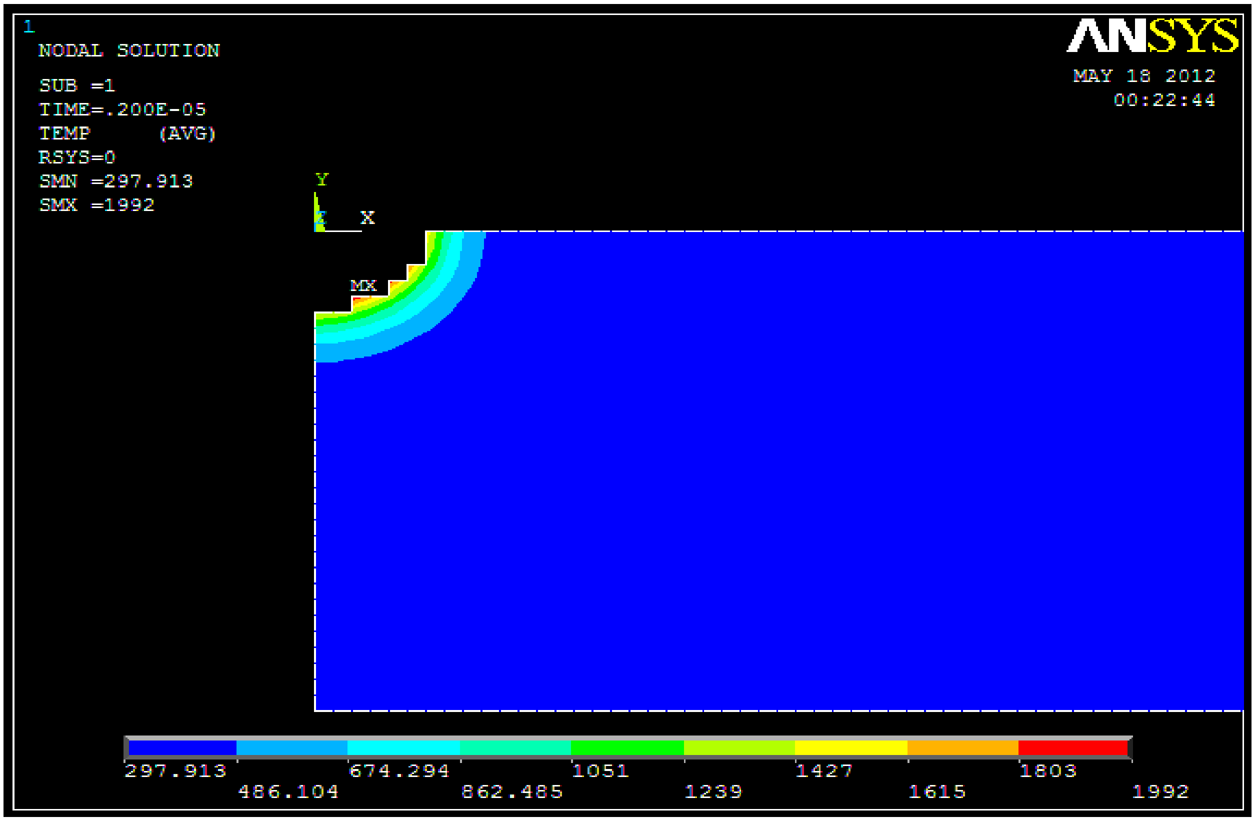


Fig. 31 MRR temperature distribution in Inconel 718 with V=20V, I=2A and P=0.09

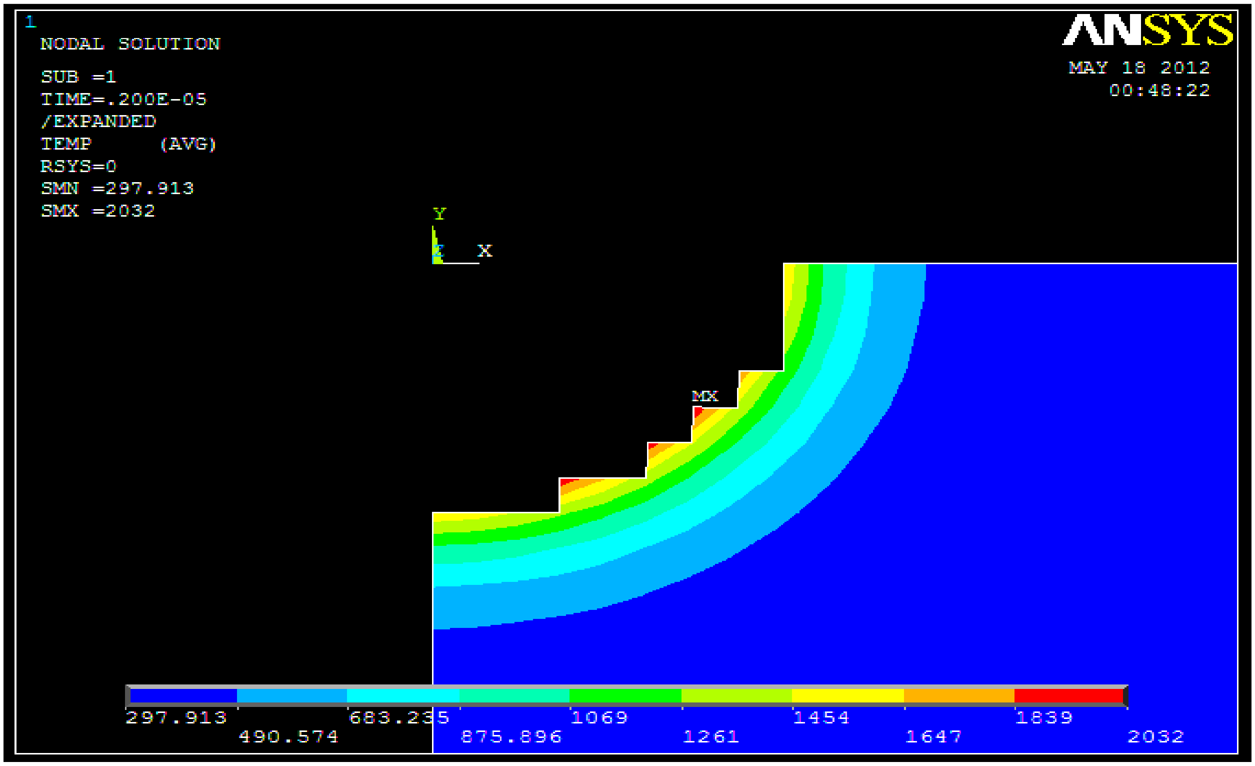


Fig. 32 MRR temperature distribution in Inconel 718 with V=20V, I=4A and P=0.16

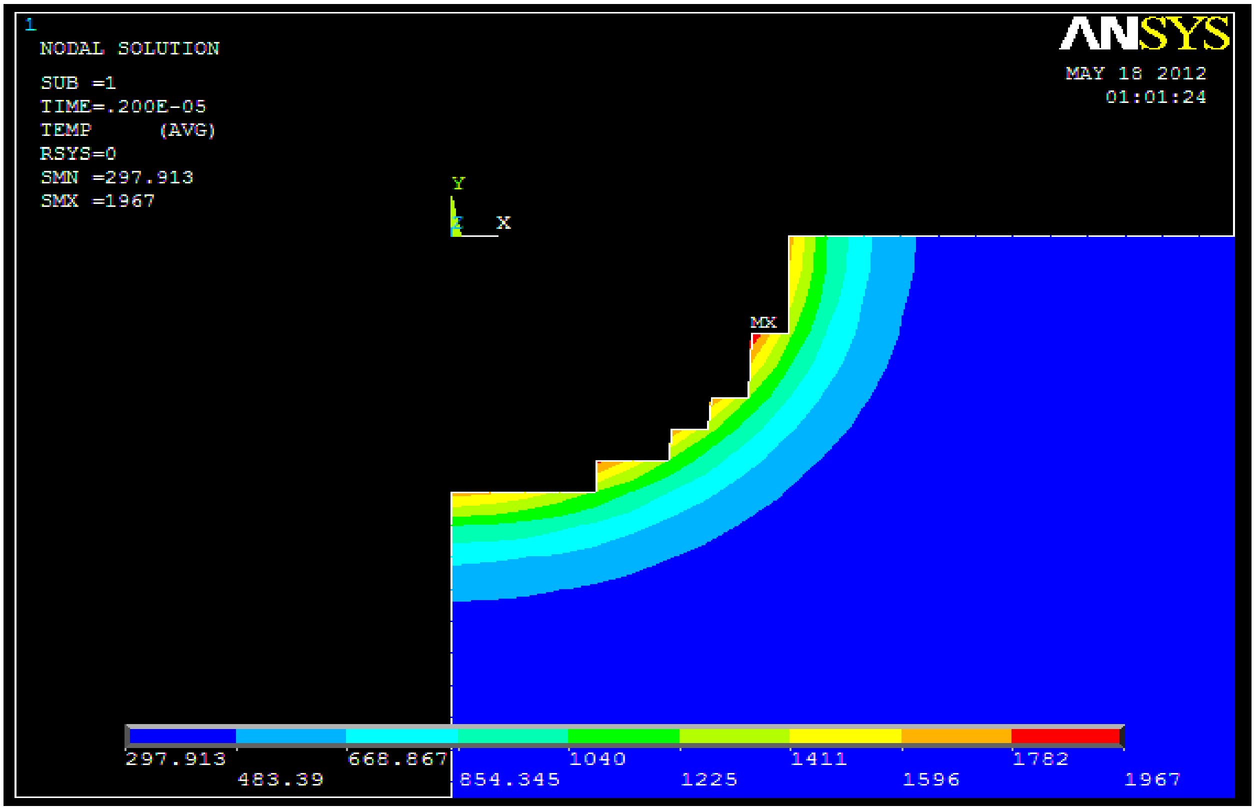


Fig. 33 MRR temperature distribution in Inconel 718 with V=20V, I=6A and P=0.20

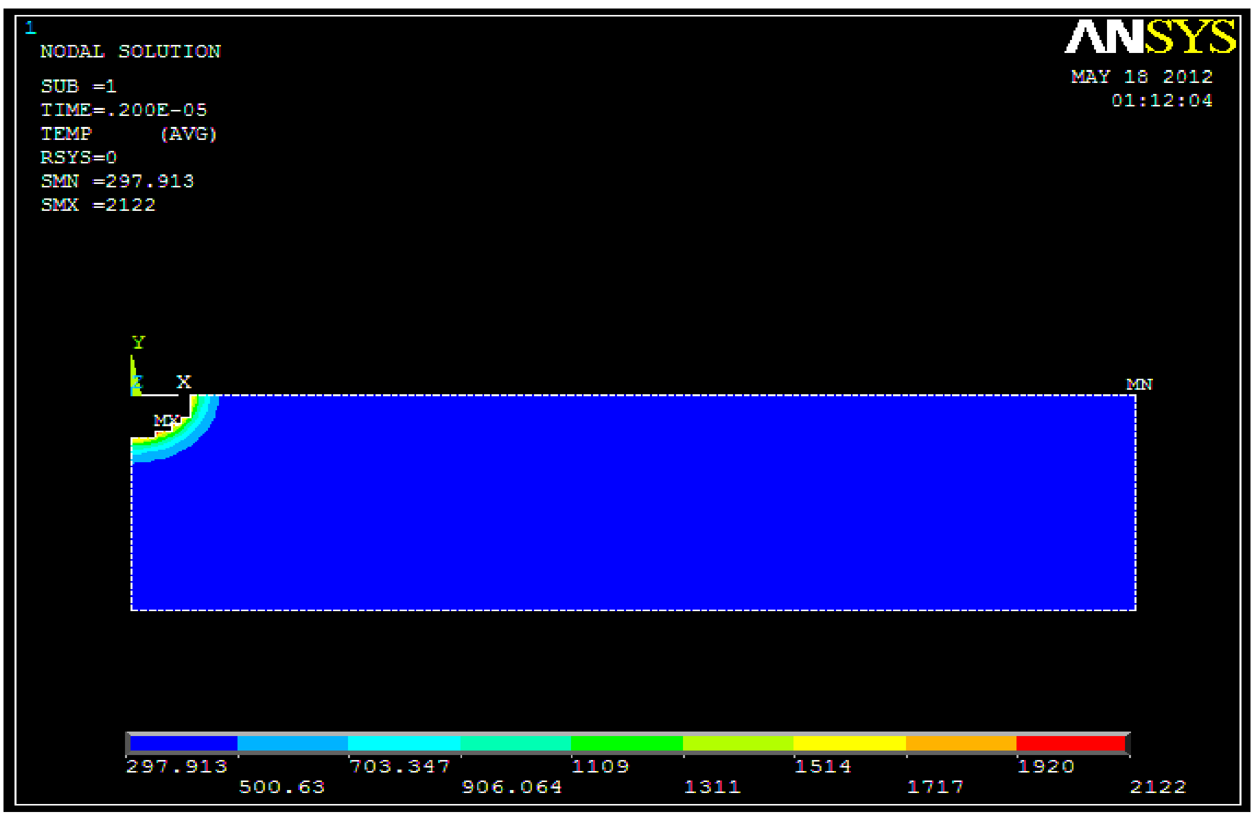


Fig. 34 MRR temperature distribution in Inconel 718 with V=25V, I=2A and P=0.16

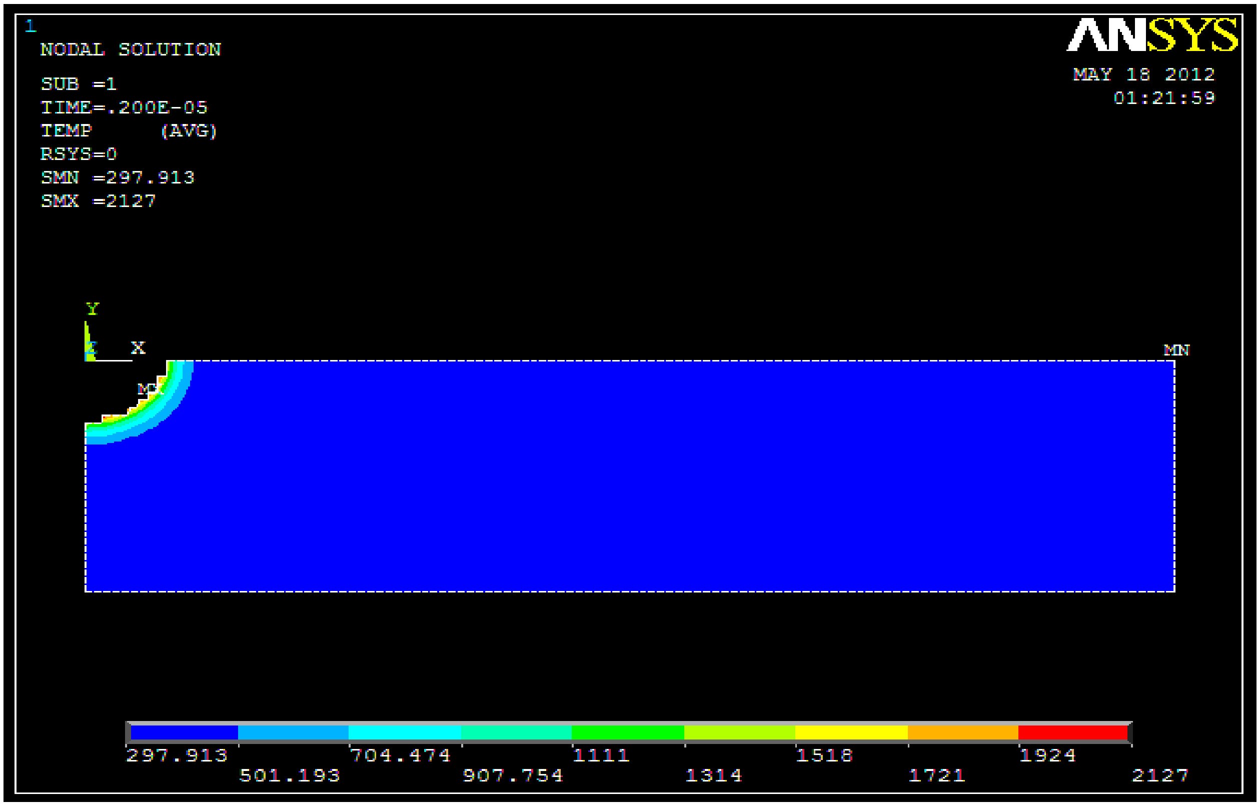


Fig. 35 MRR temperature distribution in Inconel 718 with V=25V, I=4A and P=0.20

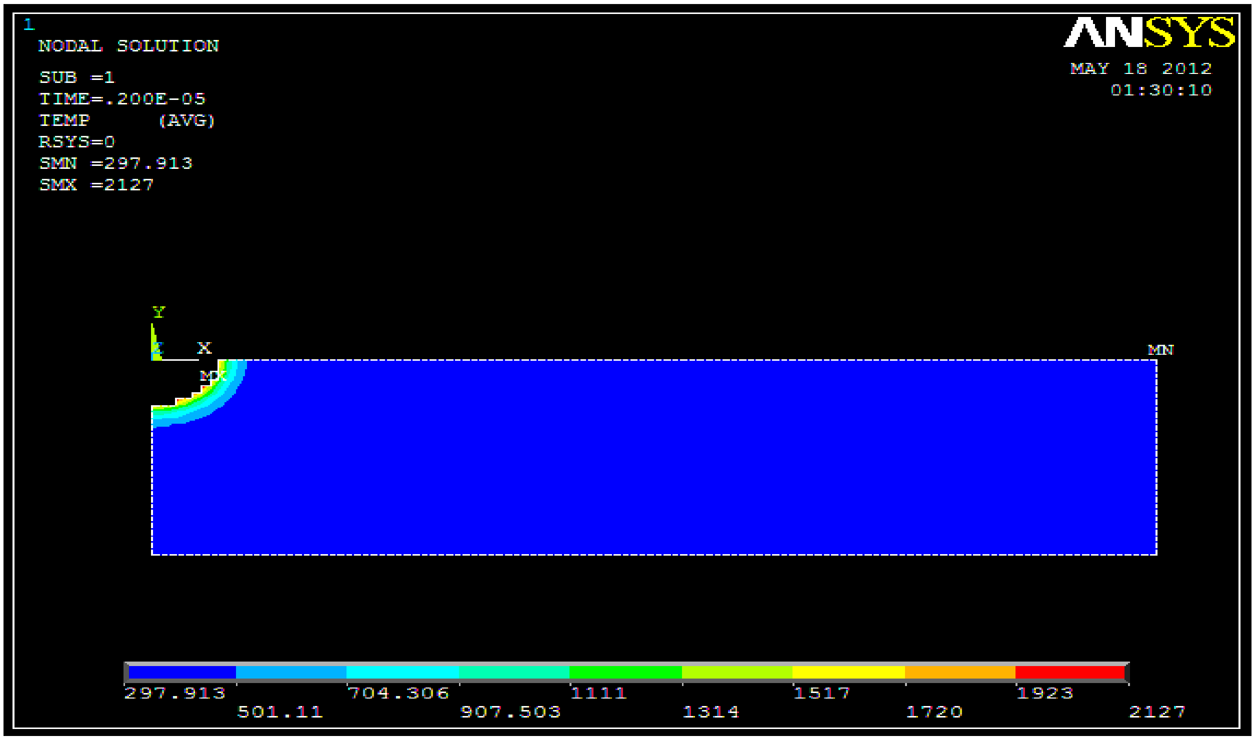


Fig. 36 MRR temperature distribution in Inconel 718 with V=25V, I=6A and P=0.09

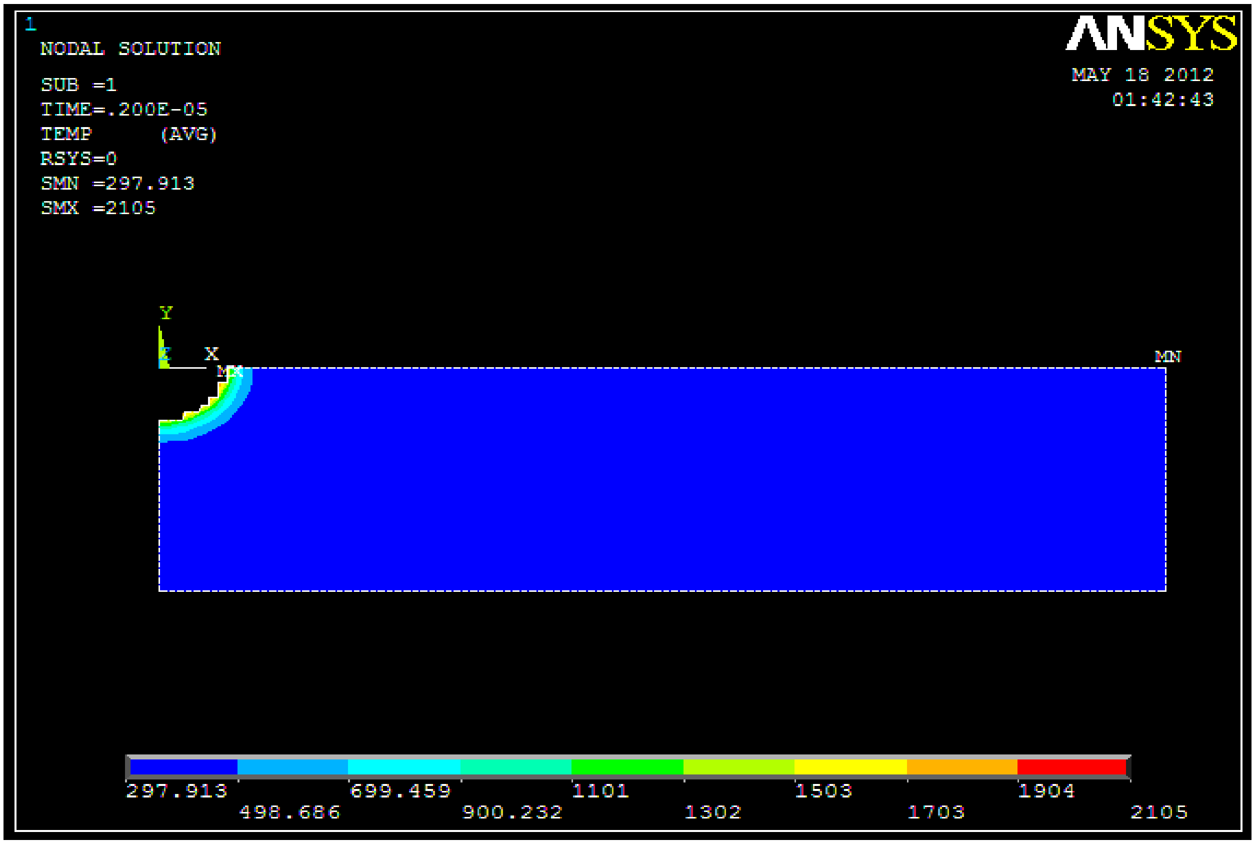


Fig. 37 MRR temperature distribution in Inconel 718 with V=30V, I=2A and P=0.20

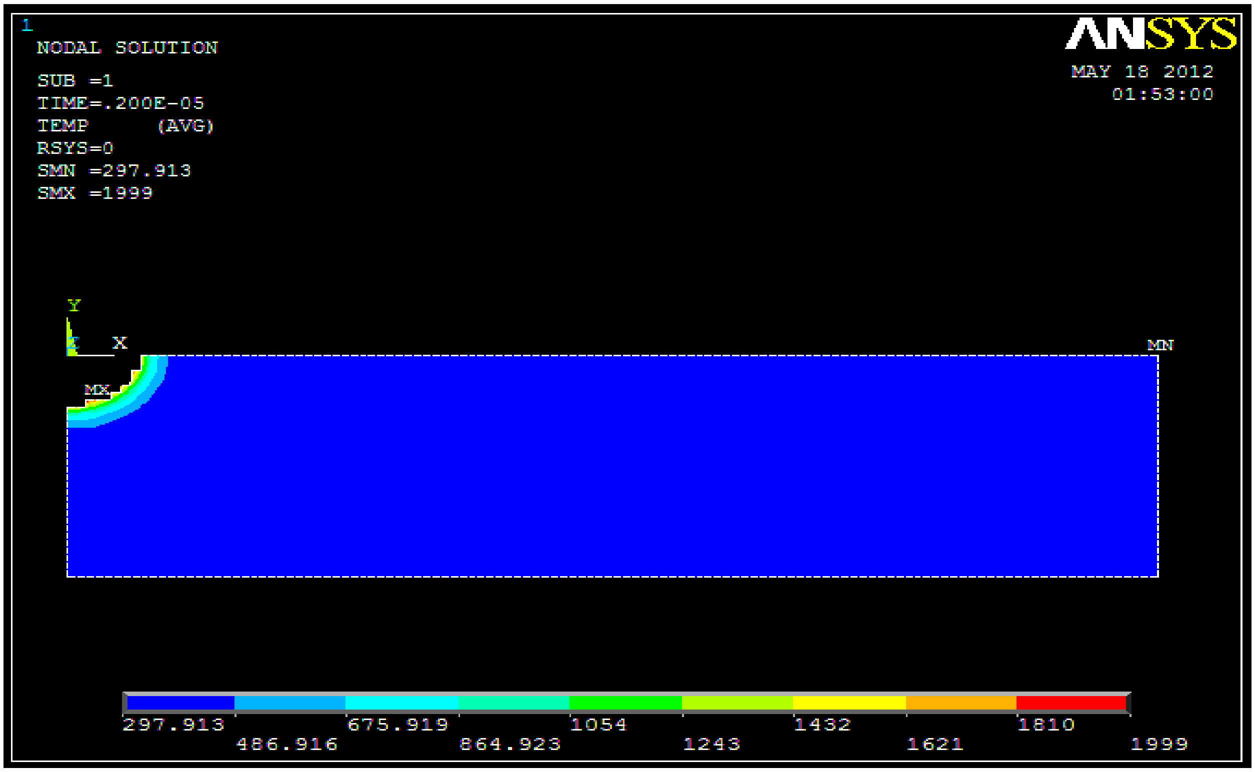


Fig. 38 MRR temperature distribution in Inconel 718 with V=30V, I=4A and P=0.09

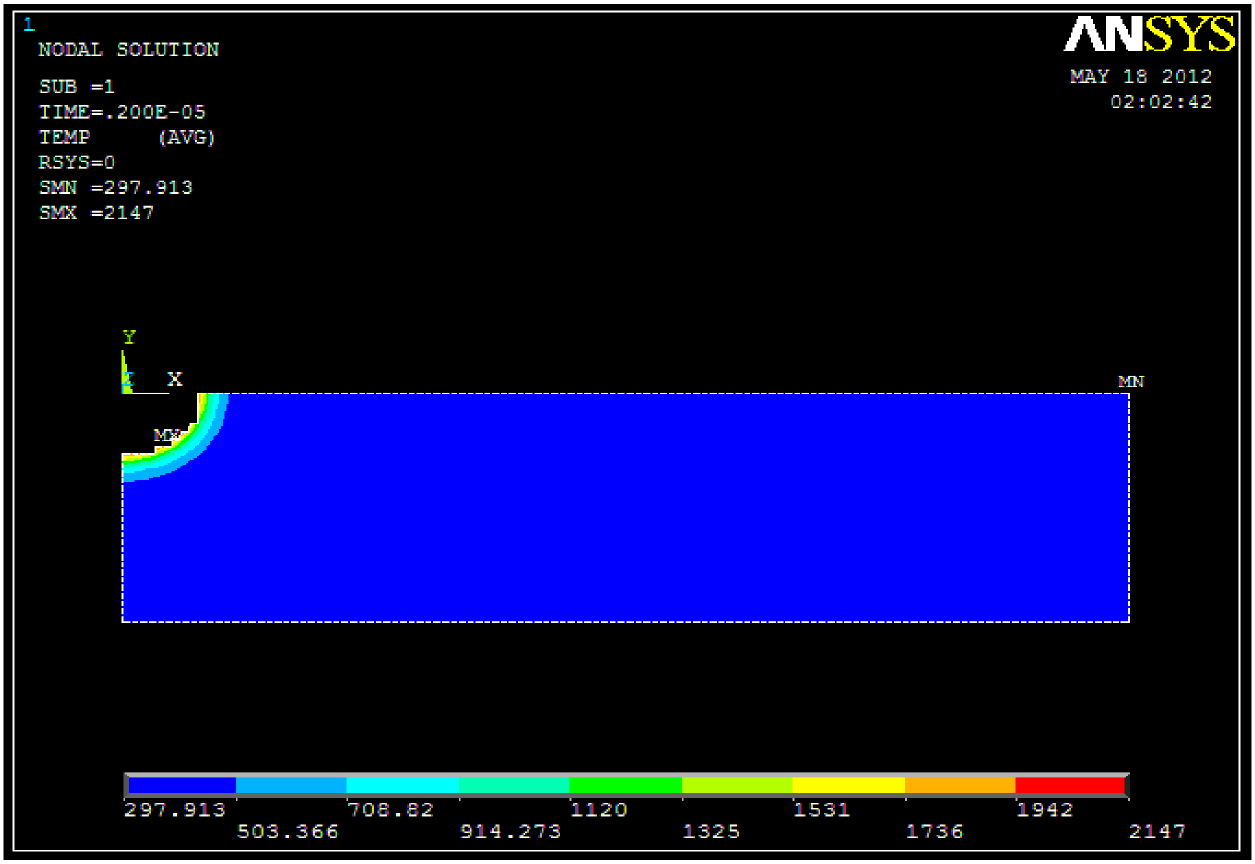


Fig. 39 MRR temperature distribution in Inconel 718 with V=30V, I=5A and P=0.15

5.5 Residual Stress modelling of micro wire EDM for single discharge

The temperature slope affected by the quick thermal cycle at the surface and thermal shrinkage of re-solidified material on the mother material, in conjunction with plastic deformation, results of the development of tensile residual stress. Residual stress trend perhaps changed by the metallurgical change relating volumetric changes, [10].

Residual stresses are self-equilibrating stresses that occur in a body if all external loads are removed. They occur when a body is subjected to uneven plastic deformations or changes of specific volume.

After we getting the result of MRR, now we finding the residual stress with the same parameters, to see that, in between the T_{off} time how much the stress will develop in the machined workpiece.

5.6 Optimization model response table for micro wire EDM process

After the getting the modeling of MRR and residual stress of micro wire EDM we come into the main response table. We analysis that for MRR the response table is higher the better and for residual stress the lower the better criteria is to be adopted

Table 19 Predicted data from ANSYS obtain from model of micro EDM for Inconel 718

S. No.	VOLTAGE	CURRENT	HEAT INPUT	MRR (single spark) (mm^3/min) x 10^{-6}	Residual Stress (GPa)	MRR (multi spark) (mm^3/min) x 10^{-3}
1	20	2	0.09	167528.55	2.83	98.546
2	20	4	0.16	478850.55	3.35	281.670
3	20	6	0.20	739285.55	2.37	434.870
4	25	2	0.16	323697.60	2.39	190.405
5	25	4	0.20	633079.44	3.15	372.400
6	25	6	0.09	502113.40	2.09	295.360
7	30	2	0.20	453452.90	3.34	266.737
8	30	4	0.09	444217.60	2.65	261.300
9	30	6	0.16	769300.00	2.56	452.529

Table 20 Response table (mean) for Fuzzy Inference Systems

VOLTAGE	CURRENT	HEAT INPUT	MPCI	SNRA1	PSNRA1
20	2	0.09	0.245	-12.2167	-0.427995
20	4	0.16	0.262	-11.6340	
20	6	0.20	0.748	-2.5220	
25	2	0.16	0.506	-5.9170	
25	4	0.20	0.476	-6.4479	
25	6	0.09	0.752	-2.4756	
30	2	0.20	0.255	-11.8692	
30	4	0.09	0.509	-5.8656	
30	6	0.16	0.759	-2.3952	

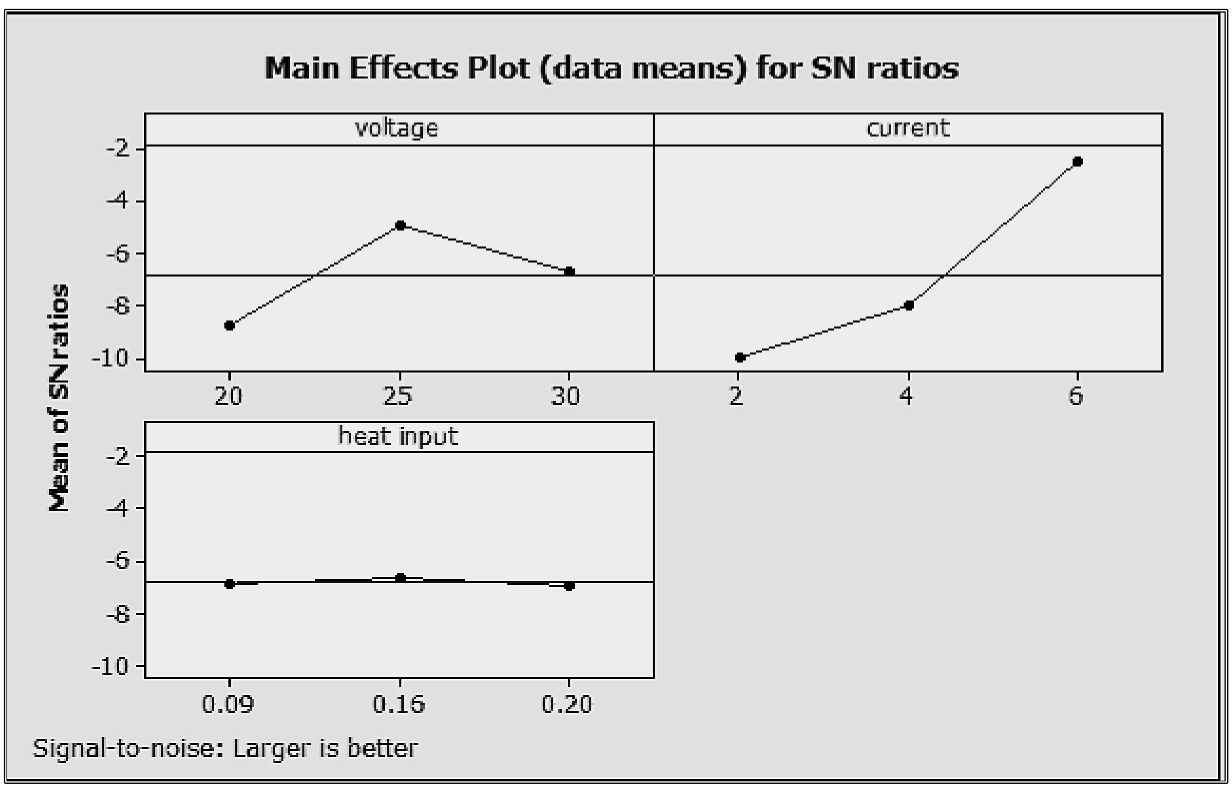


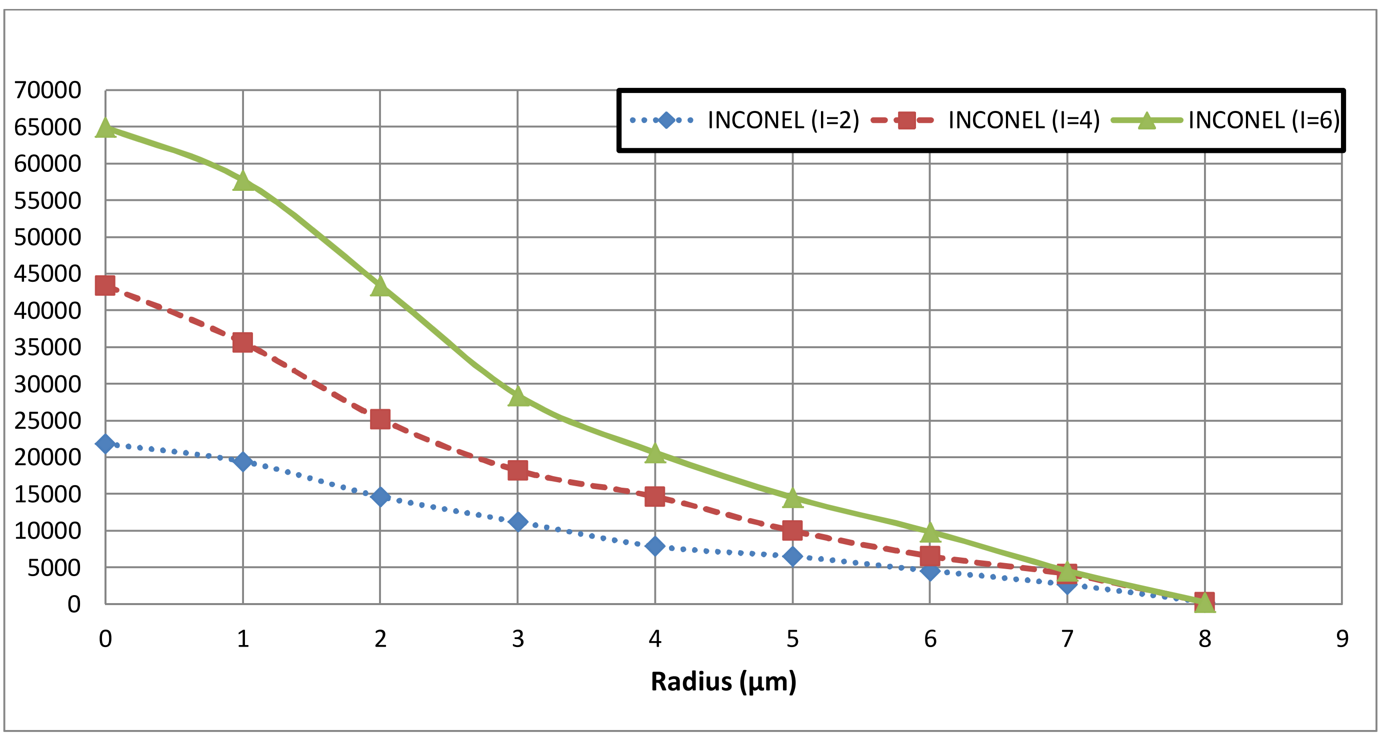
Fig. 40 Main effect plots

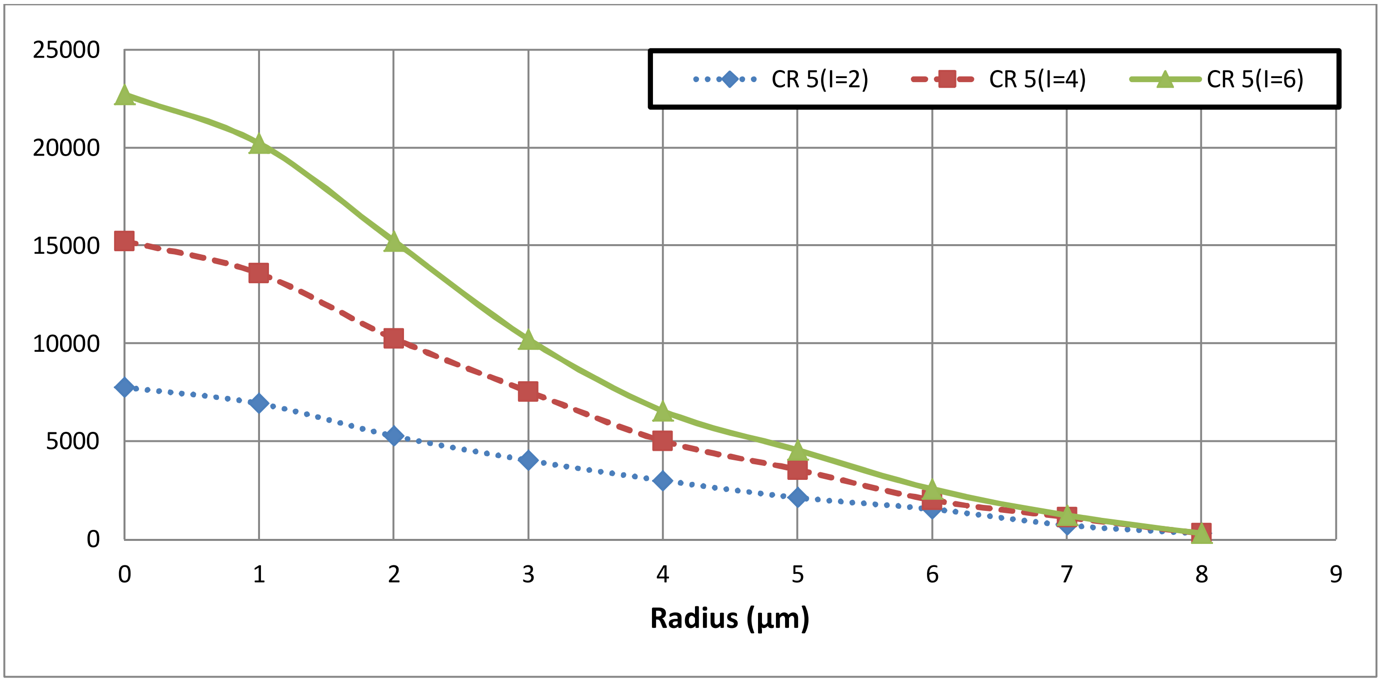
5.7 Effect of different process parameters

5.7.1 Effect of current

From the graph we observed that the temperature of the surface is going increasing as increasing the current, because of the heat flux equation which directly proportional to the current. It can be also observed that the temperature distribution follows the Gaussian heat flux distribution. Considerable as we rise temperature along the radial direction can be seen up to 8 µm.

The temperature variations along the depth of workpiece are shown in Fig. 39. It is observed that the maximum temperature is found on the surface and decreases as we proceed. No substantial variation in temperature is observed after a cut of 6 µm.





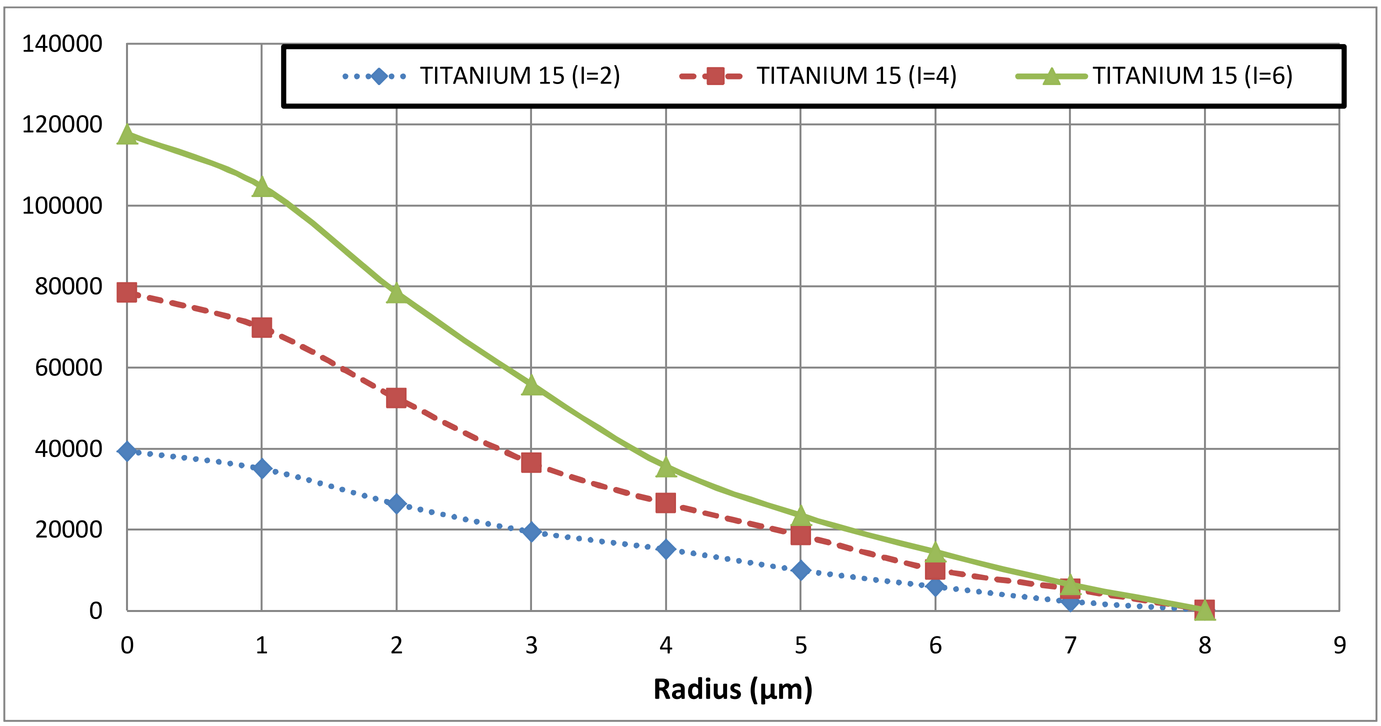


Fig. 41 The effect of current on the temperature distribution along the radial direction from the centerline for micro EDM at P = 0.09, Ton = 2 µs, V = 20 V.

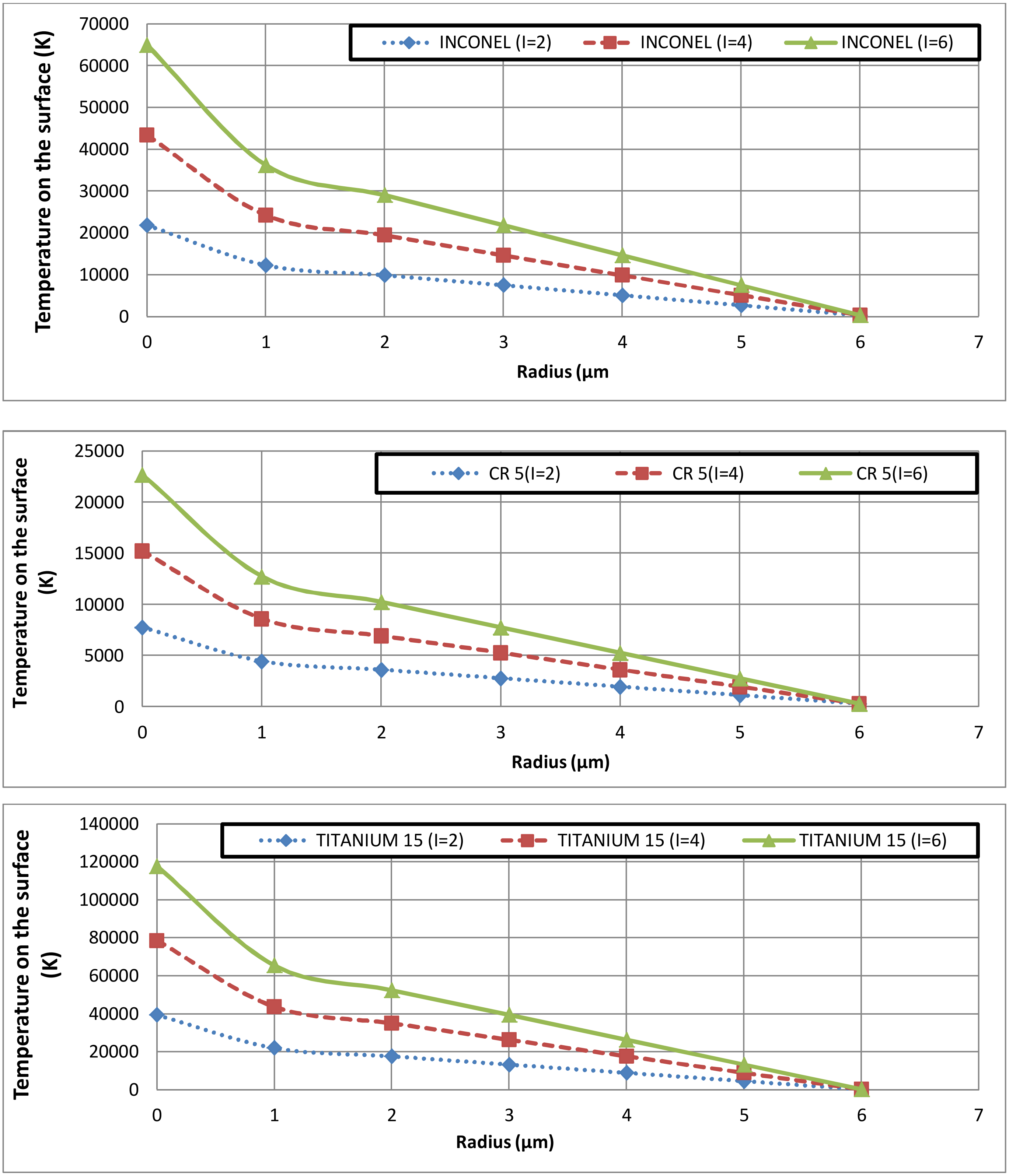


Fig. 42 The effect of current on the temperature distribution along the depth of workpieceat the centerline for micro EDM at P = 0.09, Ton = 2 µs, V = 20 V.

5.7.2 Effect of heat input to the workpiece

From the graph we observed that the temperature of the surface is going increasing as increasing the heat input, and the effect of difference of heat input to the workpiece along the radius and depth are shown in Fig. 42 and 43. From the graph, it can observed that high temperature on surface is reach at increase the heat input.

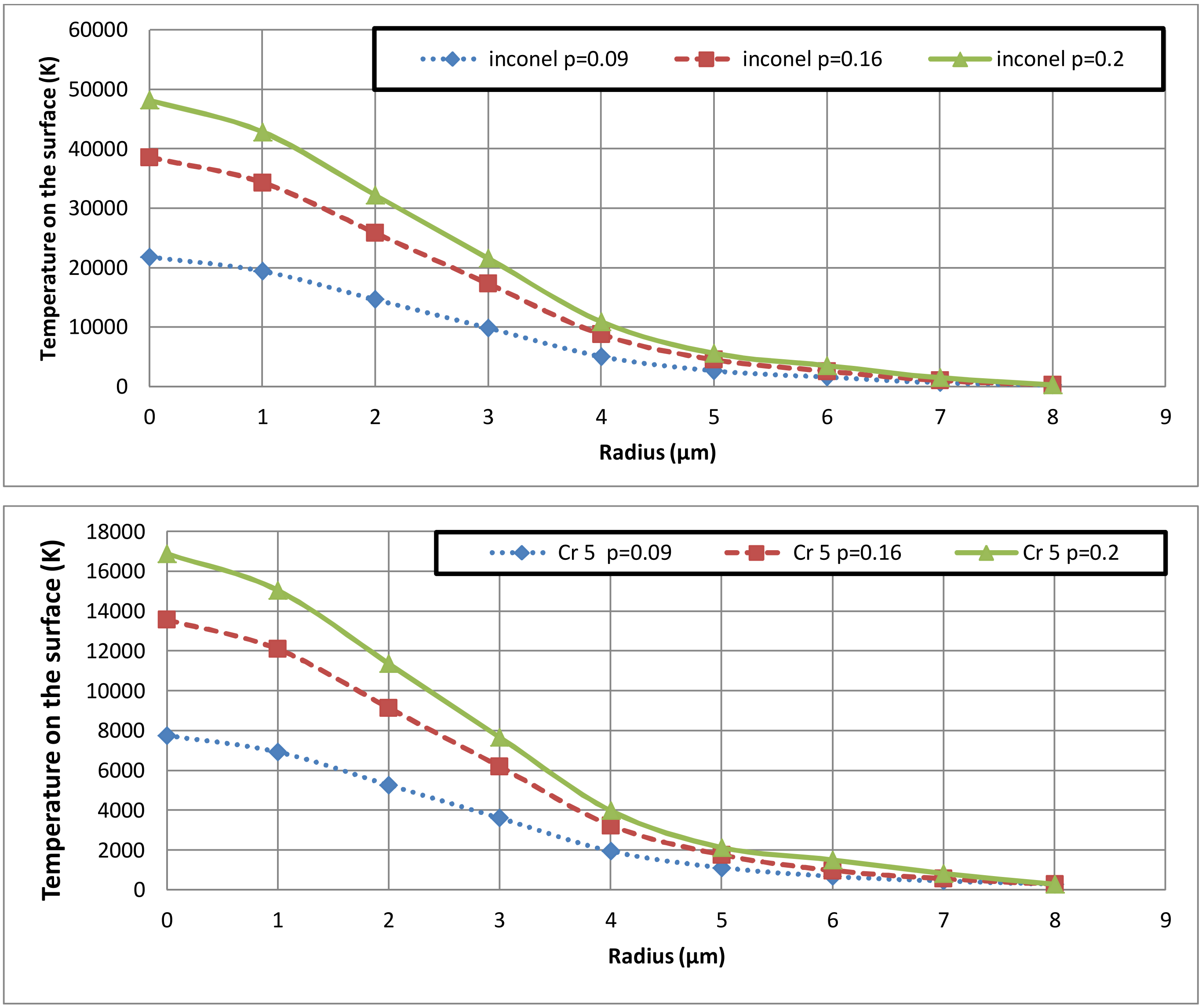
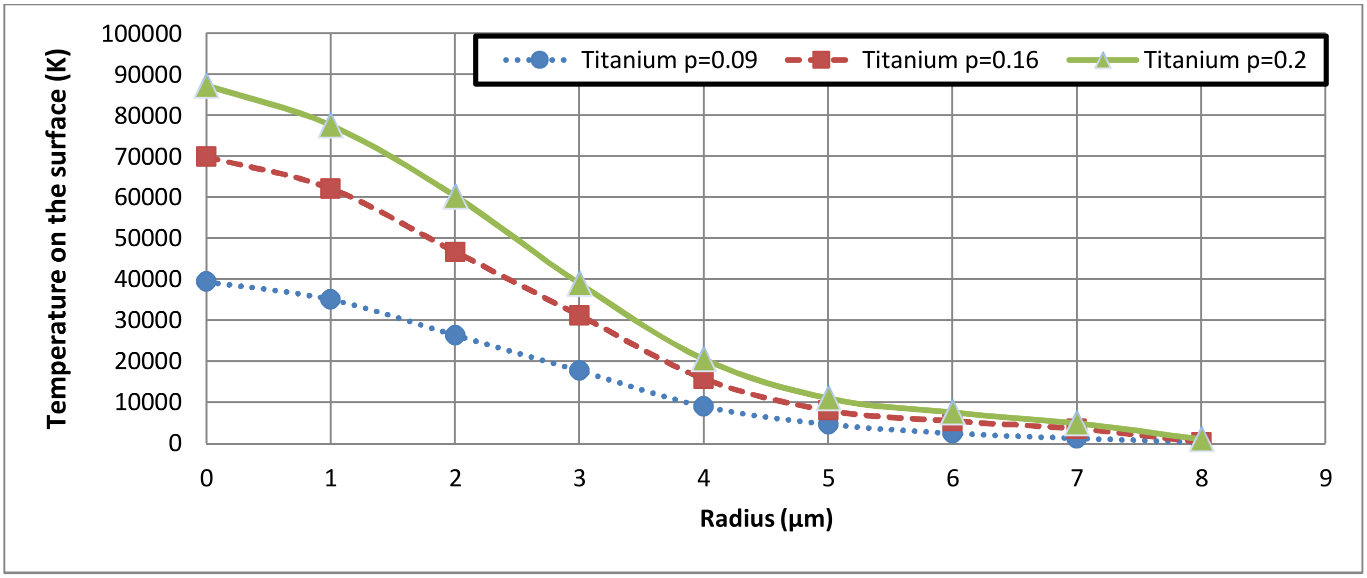
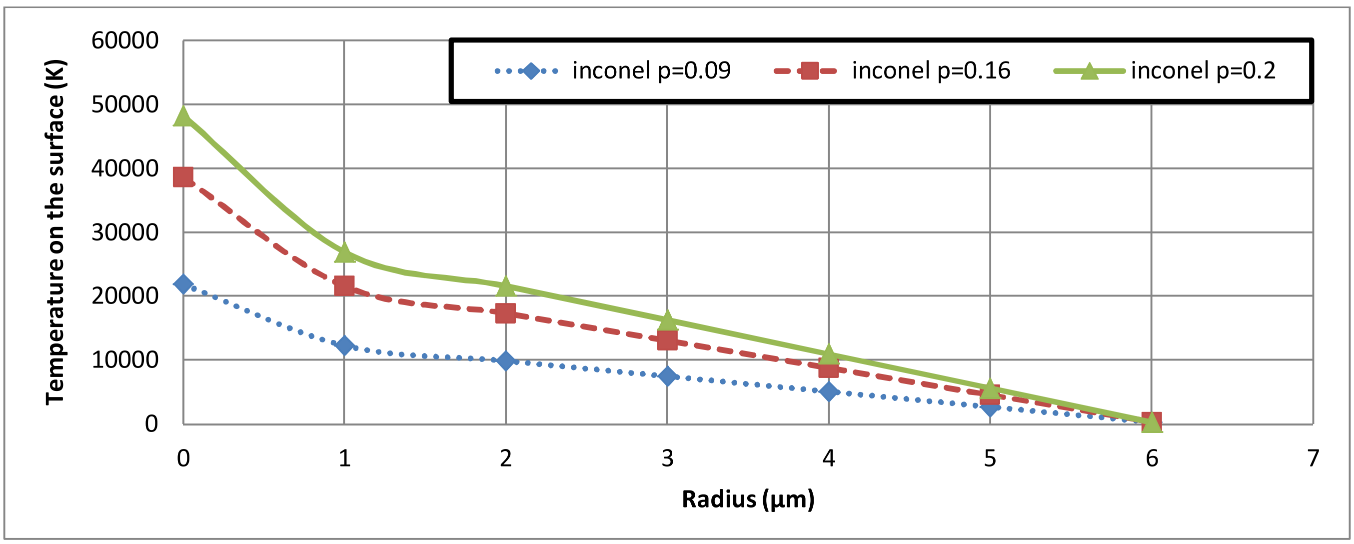
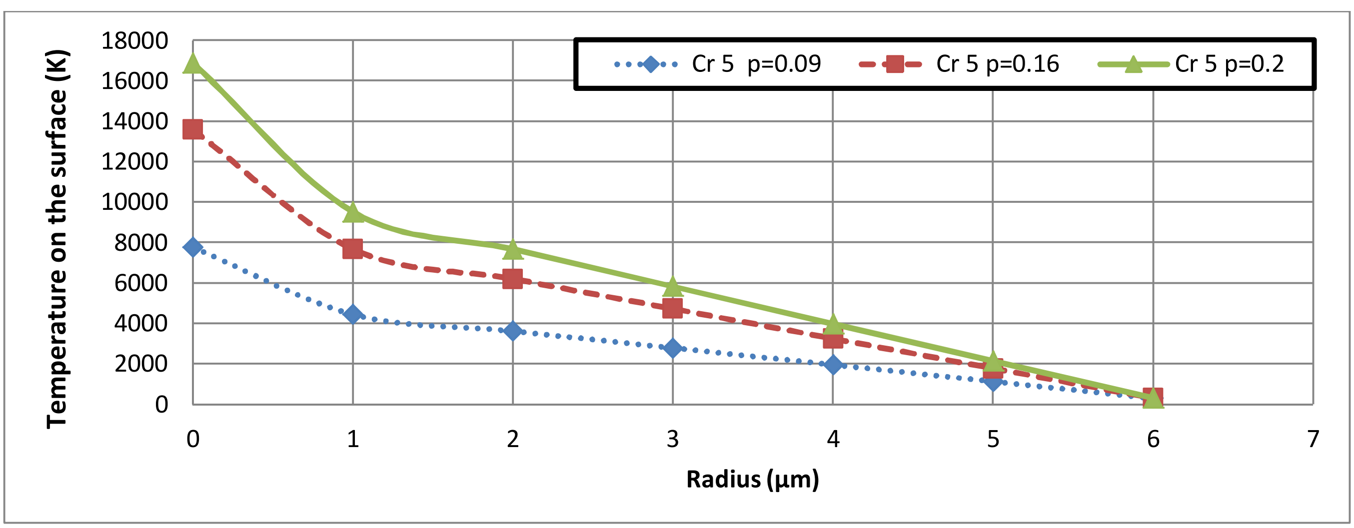


Fig. 43 The effect of heat input to the workpiece on the temperature distribution along the radial direction from the centerline for micro EDM at I = 2 A, Ton = 2 µs, V = 20V


Temperature on the surface (K)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
1
2
3
4
5
6
7
8
9
Radius (µm)
Titanium p=0.09
Titanium p=0.16
Titanium p=0.2


Temperature on the surface (K)
60000
50000
40000
30000
20000
10000
0
0
1
2
3
4
5
6
7
Radius (µm)
inconel p=0.09
inconel p=0.16
inconel p=0.2


Temperature on the surface (K)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
1
2
3
4
5
6
7
Radius (µm)
Cr 5 p=0.09
Cr 5 p=0.16
Cr 5 p=0.2

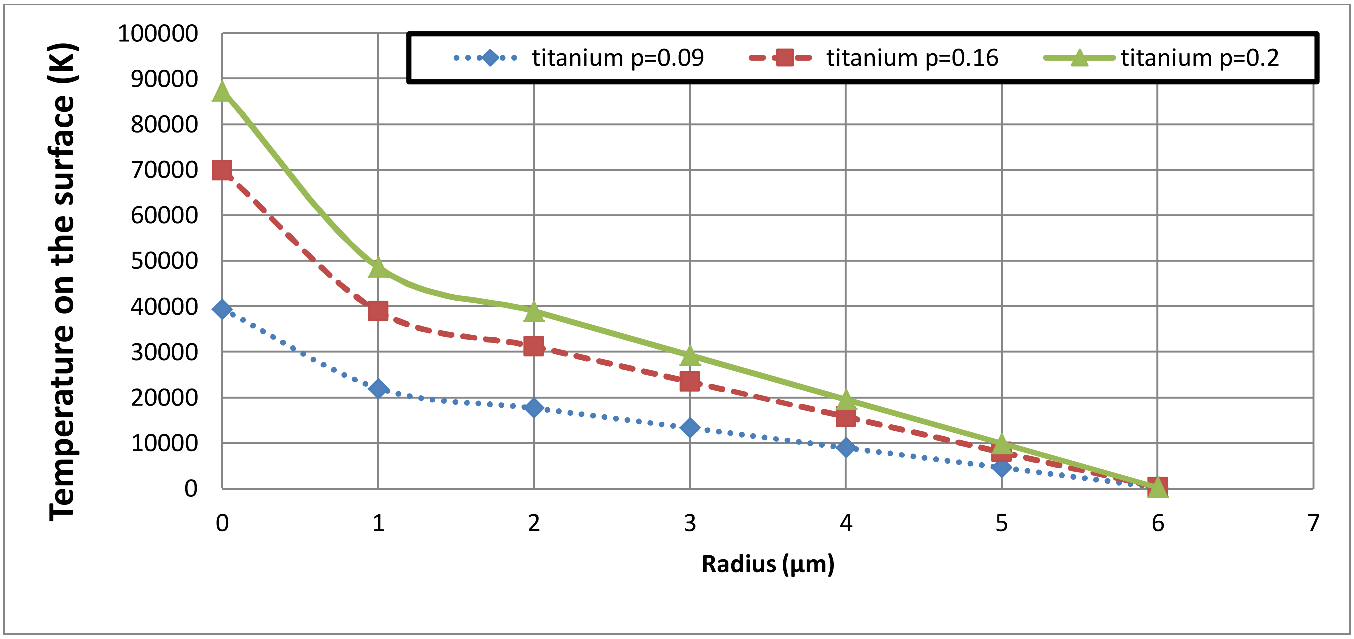


Fig. 44 The effect of heat input to the workpiece on the temperature distribution along the depth of workpiece at the centerline for micro EDM at I = 2 A, Ton = 2 μs, V = 20 V.

Chapter 6

- **Conclusions**

6 Conclusions

- **From Experimental**
  - From the S/N ratio plot the optimum parameter settings are V = 4V, I = 7A and Ton = 2μ
  - Ton is found to be the most significant factor influencing all responses investigated. Simultaneously, the opposite were observed for MRR, through which increasing of Ton will result in better rate of MRR.

- **From ANSYS modeling**
  - MRR and residual stress have been calculated for Inconel 718, titanium 15, Cr 5 die steel, for micro Wire EDM
  - Voltage Current and Percentage of heat input as the input parameter.
  - L9 orthogonal array based taguchi method has been considered to optimize the process for Inconel 718 Material.
  - The optimize parameter for fond to the Voltage = 25V, Current = 6A and percentage of heat input = 0.16.
  - MRR is found to be maximum for Inconel 718 material as comparing the titanium 15, Cr 5 die steel.
  - Residual stress induced is compressive in nature as obtain from thermal modeling from ANSYS®

- The MRR values predicted by our model are closer to the experimental results when compared with all the earlier reported analytical models.
- Residual is found maximum in Inconel 718 as comparing the titanium 15, Cr 5 die steel
- The developed thermal model can be used to carry out extensive parametric studies the micro wire EDM process carrying out, without going for actual experiments.

❖ **Single-discharge Micro wire EDM to Multi-discharge Micro wire EDM**

- For multi-discharge error from theoretical to practical in MRR is found maximum 25.06 %

Chapter 7

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